

METAL PROGRESS

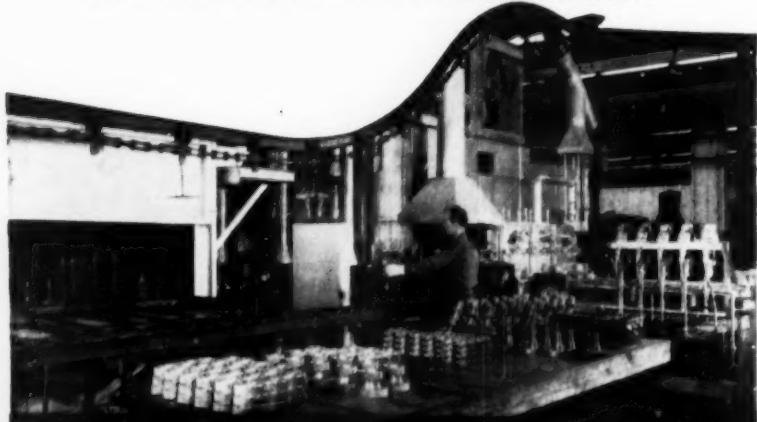


JULY 15, 1954

REPORTS OF 22 TECHNICAL COMMITTEES
OF THE AMERICAN SOCIETY FOR METALS

FORECASTS

FOR GAS CARBURIZING PERFORMANCE



You'd be amazed (as we are sometimes) at the long memories possessed by some of our furnace engineers. On short notice they'll give you the serial number, location and performance data on furnaces that we installed as long as 10 or 15 years ago — and they're generally right. The point is, the best way to forecast the performance of a furnace not yet built is to check thoroughly the records of similar installations.

BASED ON 22 YEARS OF "HINDSIGHT"

We have built hundreds of gas carburizers for all types of production requirements. If you are interested in continuous gas carburizing for instance, we can point to the first installation of its kind in 1931. It's still doing a job as reported in our sixteen-page bulletin, SC-134, an important and valuable review of gas carburizing techniques and possibilities. Write for it, on your letterhead please.

Current 'Surface' Literature

YOURS FOR THE ASKING

You may find quick answers to your immediate heat treat problems in these recent Surface Combustion Technical Library publications. Ask for the ones most pertinent to your requirements and we'll send them promptly.

bulletins

- SC-134 Modern Gas Carburizing
- SC-158 RX Prepared Atmosphere Generator
- SC-155 Prepared Gas Atmospheres
- SC-149 Pit Type Controlled Atmosphere Furnaces
- SC-147 Rotary Retort Controlled Atmosphere Furnaces

reprints

- 53-A Pit Type Carburizing Furnaces Provide Flexible Setup
- 52-C Continuous Carbon Restoration Furnace Boosts Production
- 49-E Furnaces for Gas Carburizing
- 49-B Homogeneous Carburizing
- 47-E Influence of Water Vapor on Gas Carburizing Atmospheres

SURFACE COMBUSTION CORPORATION, TOLEDO 1, OHIO

ALSO MAKERS OF

Kothaber HUMIDITY CONDITIONING

Janitrol AUTOMATIC SPACE HEATING



Metal Progress

July 15, 1954

Vol. 66, No. 1-A

Two issues of *Metal Progress* are being sent to all ASMembers and subscribers in July: The one dated July 1, 1954 has the usual editorial direction. This one, dated July 15, 1954, is confined to reports of 22 technical committees, and, as noted in *Metal Progress* for June, 1954, p. 200, it can be used to supplement the 1948 edition of the A.S.M. Metals Handbook.

Metals and Applications

The Selection of Constructional Steels

Engineering considerations. Fatigue. Brittle failures. Hot rolled and cold drawn steels. Carbon, alloy and low-alloy steels. H-steels and hardenability. Selection of carbon content. Tensile properties. Steels for case hardening. Standards and compositions.

The Selection of Tool Steels

Principal types of tool steels. Factors in selection. Cutting tools. Die blocks and inserts. Tools for forging, trimming, hot extrusion. Dies for drawing, blanking and piercing, press forming, coining, cold extrusion, cold heading, thread-rolling. Gages. Plastic molds. Die-casting dies and permanent molds.

Stainless Steels

Wrought alloys—austenitic, martensitic and ferritic steels; corrosion resistance; welding. Castings—design and selection; welding; machining.

Heat-Resisting Alloys

Short-time tension tests. Stress-rupture. Creep. Relaxation. Design curves. Impact. Fatigue. Vibration. Damping capacity. Design considerations. Alloy data.

Nodular Cast Iron

Processing. Stress relieving and ferritizing anneal. Structures; hardenability; machinability. Physical and mechanical properties. Applications.

Applications of Aluminum and Aluminum Alloys

Aircraft, automotive, railroad, and marine applications. Electrical appliances, furniture, construction, and chemical process applications. Properties of 20 aluminum alloys.

Selection of Copper and Copper Alloys

Wrought forms—electrical conductivity; thermal conductivity; mechanical strength; formability; machinability; surface finish; joining; corrosion resistance. Castings—castability; machinability; mechanical properties; bearing and wear properties; corrosion; electrical and thermal conductivity.

Magnesium and Magnesium Alloys

Production and use. Processing trends. Cleaning and finishing. Application, design and selection. Fatigue considerations. Applications at elevated temperatures. Protection of assemblies. Properties of six magnesium alloys.

Titanium and Titanium Alloys

Production of ingots and mill forms. Forging, forming, machining and grinding. Welding, heat treating, cleaning and finishing. Corrosion resistance; metallurgy. Applications. Properties of titanium and titanium alloys.

Table of Contents Continued on Page A-3

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Here's help in Ordering

THERMALLOY*

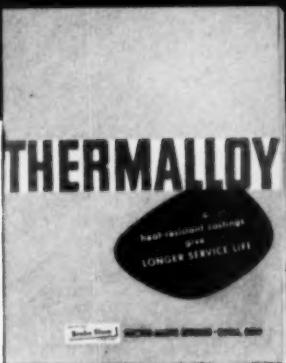
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Centrifugal
Castings Bulletin



General Thermalloy
Catalog T-225

THERMALLOY



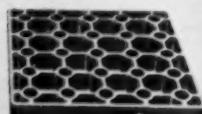
Muffles & Retorts
Bulletin T-239



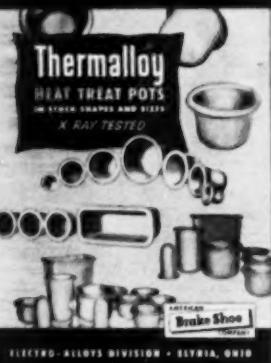
Conveyor Belt
Bulletin T-241

Thermalloy

heat-treat trays and fixtures



Heat Treat Trays & Fixtures
Bulletin T-227

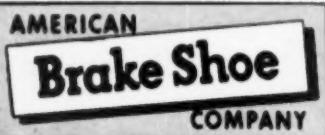


Heat Treat Pots
Bulletin T-234

Wherever high heat and special atmospheres are problems in heat-treating or processing equipment, Thermalloy heat-resistant castings can help to minimize expensive repairs, high maintenance costs, sudden breakdowns.

To help you in ordering Thermalloy heat-

resistant castings for use in many different types of equipment, you will find assistance in these bulletins. To obtain the bulletins pertaining to your problem, call your nearest Electro-Alloys representative or write Electro-Alloys Division, 5002 Taylor St., Elyria, Ohio.



ELECTRO-ALLOYS DIVISION
Elyria, Ohio

*Reg. U. S. Pat. Off.

Table of Contents Continued

Design and Application

Engine Metals and Engine Wear	91
Cylinders and liners. Pistons and piston rings. Camshafts and tappets. Valves, seats and guides. Piston pins. Bushings. Crankshafts. Bearings. Water pump shafts.	

Effect of Stress Concentration on Design Strength	97
---	----

Service failures. Definitions and basic concepts. Application to design. Notch sensitivity. Reducing effects of stress concentration.

Shot Peening and Other Surface Working Processes	104
Fatigue improvement. Processes—explanation, selection, control.	

Design of Ferrous Castings	109
Designing with gray, white, malleable, nodular irons and with steel.	

Design of Brazed Joints	115
Metals. Clearance. Strength. Fatigue. High temperature.	

Processing and Testing

Carbonitriding	124
The process. Equipment. Atmospheres. Composition and hardness of case. Tempering. Advantages and disadvantages. Cost factors.	

The Agitation of Quenching Mediums	126
Effect of flow rate of oil. Correlation curves for water, oil and molten salt.	

The Cost of Heat Treating	128
Recommended procedures for determining costs. Cost of hardening a carburized pinion gear. Comparative costs of gas and pack carburizing.	

Selection of Metal Cleaning Methods	131
Removing drawing compounds from sheet steel; removing other types of soil; chips and cutting fluids; polishing and buffing compounds; scale. Health hazards.	

Press Forming of Sheet Steel	134
Cost and limitations. Short-run, medium and high-production tooling.	

Machining of Steel and Cast Iron	141
Cutting speed and tool life for minimum cost or maximum production.	

Machining, Joining and Finishing of Powder Metal Parts	151
Drilling. Tapping. Reaming. Turning. Boring. Milling. Shaping. Grinding. Burnishing. Coining. Joining. Impregnation and infiltration. Heat treating. Finishing.	

Steel Melting	154
Bessemer process. Basic open hearth. Basic electric furnace. Oxygen treatment. Ingot and pouring practice. Continuous casting. Vacuum and atmosphere melting.	

Selection of Methods for Nondestructive Inspection	159
Methods. Evaluating soundness of welds. Detecting cold shuts. Inspection of heat-resisting metals. Sorting mixed lots of steel.	

Metallography	164
Principles of the metallurgical microscope. Reflecting objectives. Photomicrography in color. Electrolytic polishing and etching. Cathodic vacuum etching. Phase contrast, ultraviolet and electron metallography.	

Biographies of members of Metals Handbook Committee and chairmen of sub-committees	A-92
--	------

Digests of Important Articles

The Notched Slow-Bend Test (p. A-139). Stress-Corrosion Resisted by Additions of Ti and Ta-Cb (p. A-140). Tubing Welded Faster with Less Power (p. A-146). Causes of Filiform Corrosion (p. A-150). X-Ray Measurements of Lattice Distortions in Martensite (p. A-154). Failure of Structural Sections in Welded Ships (p. A-156). Mathematics in Quality Control (p. A-166). Quality of Extrusions (p. A-170). Evaluate Oxalic Acid Etching Test (p. A-176). Deoxidation of Iron by Silicon (p. A-182). Stretcher-Strain Marks in Al-Mg Alloys (p. A-188). Alloys for High Temperature (p. A-191). Protective Behavior of Paint Primers (p. A-193).

Departments	Data Sheet; Temperature Conversions	114-B
-------------	---	-------

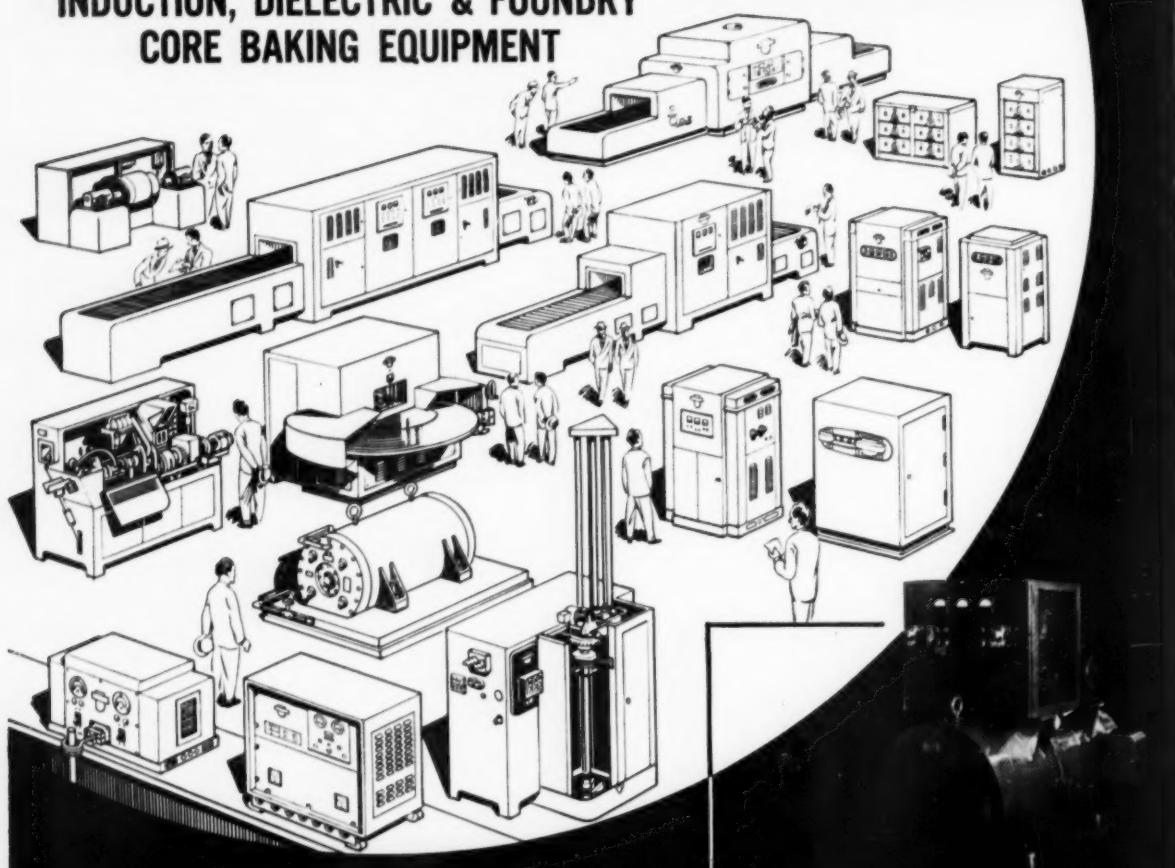
As I Was Saying, by Bill Eisenman	A-5	Index	178
-----------------------------------	-----	-------	-----

Manufacturers' Literature	A-21	Advertisers' Index	A-196
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**... the most complete line of
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High Frequency Heating by cutting production costs, enables you to pace today's competition! Use it to braze, solder, harden, anneal, forge or melt...to bake foundry cores...to preheat or cure plastics...to process foods, chemicals, textiles, wood, paper, etc.

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capacities up to 250 KW**

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As I was saying...



IT'S A PLEASURE to present in this issue of *Metal Progress* the first supplement to the '48 edition of the Metals Handbook, and also it seems like the appropriate time and place to bring many of the new members (those who have joined within the last 25 years) up to date on the early history of this notable work. It was in 1918 that I first heard of the beginnings of the A.S.M. from Ted Barker, then president of the Board of Education of Elmhurst, Ill., where I was superintendent of schools (believe it or not) with some 50 first-grade teachers, one of whom (Mill) I took out of my system and made my assistant and later my manager.

So here I was, selected to become head of the Public School System of Memphis, Tenn., the following September, but listening to my valued

employer and friend enticing me away from school work into the realm of association activity. The interesting thing about it was that at the time Ted was selling us on the idea there was no association or society in existence—it was only an idea in the minds of a few metalmen, who represented a group of 200 which had had one meeting and had become enthusiastic about the possibilities of a national organization with chapters in industrial centers, with a headquarters staff, with a data sheet service, a research laboratory and other services for the metal industry.

Ted's request that I give up the educational field and attach myself to industry made a very profound impression and within a short time I was traveling hither and yon bringing a few interested individuals together and discussing the advisability of organizing a chapter of this new Society. This group was not requested to give a decision until after a sumptuous steak dinner and cigars—and in that way I always secured a unanimous decision to organize a chapter. Just one week later at the first meeting of the newly organized chapter I would present my talk, "Heat Treatment, Past, Present and Future". The past dealt with the goat, the tea leaves and the tub plus the red-headed boy. The present concerned the floating potato guide, the north-south quench and the efficiency of the quenching water from Sheffield and the Mississippi, while the future told of what the young Society hoped to do—fine publications, chapter meetings, data sheets, etc.

Having promised data sheets to all organized groups, I set about trying to do something about it. In those early days there was great secrecy about how as well as why certain metal treating and working operations were carried on and information was released reluctantly, if at all. The officers of the Society, while believing most strongly in the handbook-data sheet promise were nevertheless cautious in initiating it.

However, I still felt the idea was workable and I kept right after each successive president trying to get permission for a fresh start. It was finally secured when I was attending the S.A.E. winter meeting in New York, and I was so elated I hopped the next train to Washington, D.C., and was soon in the office of the first vice-president of the Society, Dr. George K. Burgess, head of the Bureau of Standards. He was sympathetic to my pleas and soon I was in the office of a bright, energetic, enthusiastic and up-and-coming young man by the name of Herbert J. French of the Metallurgy Division of the Bureau (president in '43), who agreed to act as editor of the data sheets and was to receive \$5.00 for each page prepared. (I hope there will be no Congressional investigation to find out what H.J. did with this additional salary.)

So we were on our way. The first batch of "Lefax" size sheets (5x3 in., 6-point type) was distributed in September 1923 and after that they were mailed monthly to the members, until September 1928 when the first bound handbook was issued. Since '28 each and every edition has shown commendable advancement and each and every edition has received more and more acclaim until we are all mighty goll-darn proud. Thousands of members have contributed time and thought to this 300,000-word \$100,000 first supplement to the last edition. We all appreciate their splendid cooperation and thank them heartily for their splendid contribution to this

BIBLE OF THE METALS INDUSTRY

Cordially,

Bill

W. H. EISENMAN, *Secretary*
AMERICAN SOCIETY FOR METALS

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operations?



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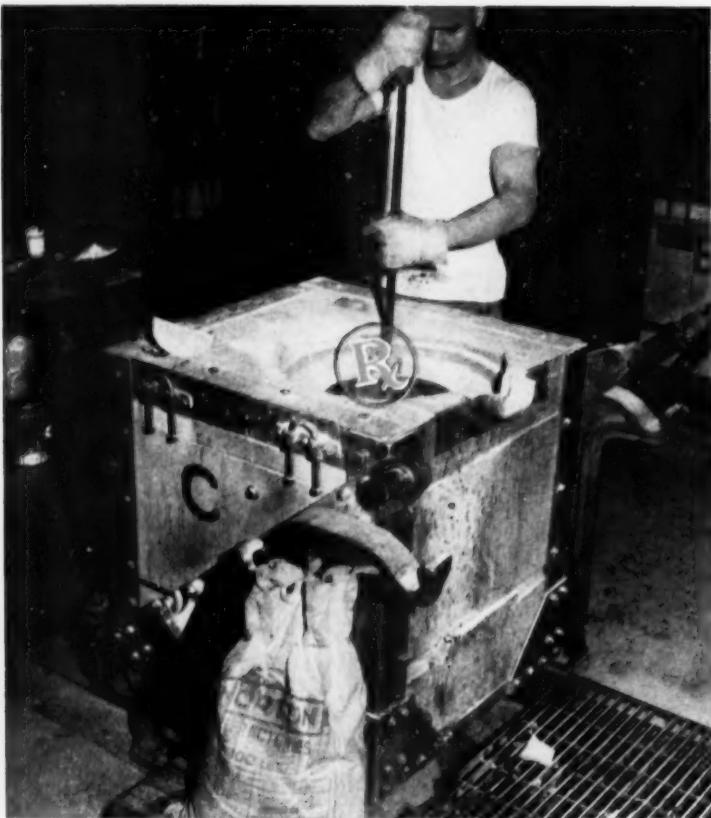
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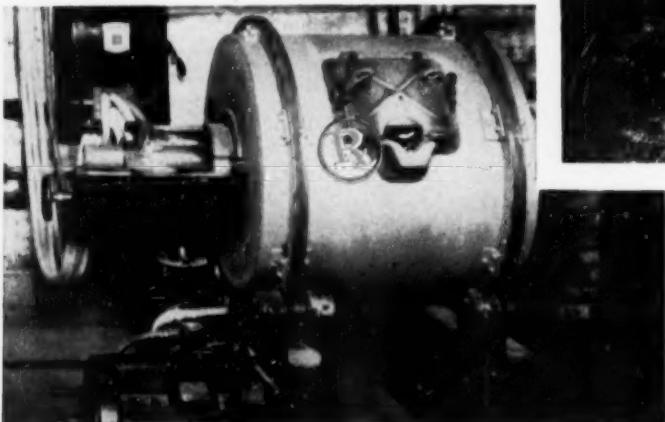
R for Rx



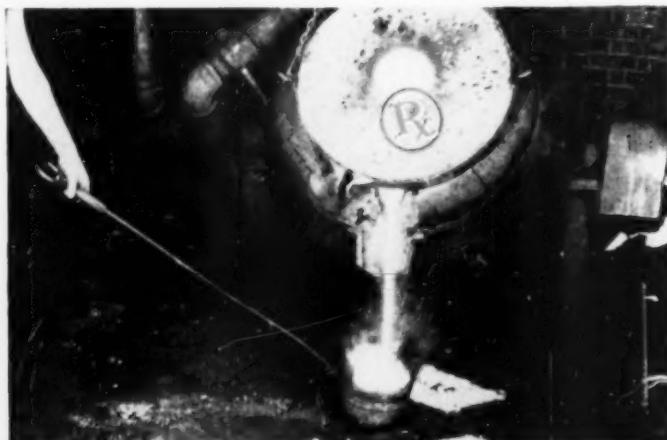
For High Frequency Furnaces. Norton MAGNORITE cement has been especially engineered for dry ramming and for withstanding temperatures up to 3250°F. Also, its slight expansion on maturing eliminates shrinkage cracks which might lead to furnace failure. It's the ideal prescription for lining high frequency induction furnaces handling melts of high temperature alloys.

Other Norton refractories for high frequency furnaces include FUSED STABILIZED ZIRCONIA crucibles for melting platinum and its alloys. They are not wetted by the metal, enabling you to recover 100% of the melt without destroying your crucibles, or to re-use the crucibles for different alloys without contamination.

For Crucible Type Furnaces. The cover of this tilting crucible furnace and its cement lining are both made of CRYSTOLON refractory material, engineered for the user's particular needs. CRYSTOLON linings offer effective protection against flame erosion and thermal shock.



For Low Frequency Furnaces. The furnace shown here has a special MAGNORITE cement lining. ALUNDUM cement is also widely used in low frequency induction furnaces. Whatever you're melting, including such refractory alloys as cupronickel and nickel silver, high copper alloys and Al, Te and Si bronzes, one of these two Norton B's is engineered to give you longer lining life — plus the high rammed density that resists metal penetration, erosion and chemical attack.



For Indirect Arc Furnaces. This installation owes much of its high production rate to its lining of correctly-engineered ALUNDUM cement. More and more foundries report excellent results with ALUNDUM and MAGNORITE crocks, covers and cements — engineered and prescribed for their individual metal processing needs. Norton prescriptions will save you time, trouble and money, too!

higher production . . . better products . . . lower costs

**Norton refractories are engineered
for top performance—prescribed for
many metal processing applications**

Norton refractory products are *engineered* to give you the best possible **B's** — the most effective combinations of physical, chemical and thermal characteristics — for your particular refractory uses.

Norton ALUNDUM*, CRYSTOLON*, MAGNORITE* and FUSED STABILIZED ZIRCONIA refractory materials are made into shapes and cements to meet your requirements. For the **B's** you need to improve your processing — and for expert aid in any refractory problem — call in your Norton Refractories Engineer. And write for helpful literature to NORTON COMPANY, 325 New Bond Street, Worcester 6, Mass. Canadian Representative: A. P. Green Fire Brick Co., Ltd., Toronto, Canada.



REFRACTORIES

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Making better products...to make other products better

*Trade-Marks Reg. U. S. Pat. Off. and Foreign Countries

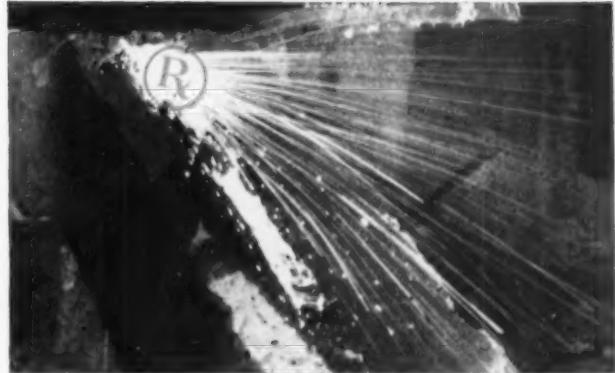
Other Norton Prescriptions

are helping metal processing plants to maintain schedules with minimum shut-downs. For example:

Heat-Treating And Sintering Furnaces operate at higher temperatures and lower costs, thanks to a wide variety of ALUNDUM and CRYSTOLON refractory products. Hearth plates, pier brick, burner blocks, muffles, muffle plates, skid rails, recuperator tubes, burner-tunnel and embedding cements combine high refractoriness with excellent thermal conductivity and resistance to spalling, erosion and corrosion.

Desulphurizing Ladles which require addition of sodium carbonate gain consistently longer lining-life when ALUNDUM cement is used. One gray iron foundry, using a 1500-lb. U-type ladle reports that ALUNDUM cement lasts two to four times longer than other linings, month in and month out.

Steel Ladles show equally successful results when lined with ALUNDUM cement. One plant, using it in a 1000-lb. teapot ladle to handle stainless steel, stepped up the number of heats from 47 to 103.



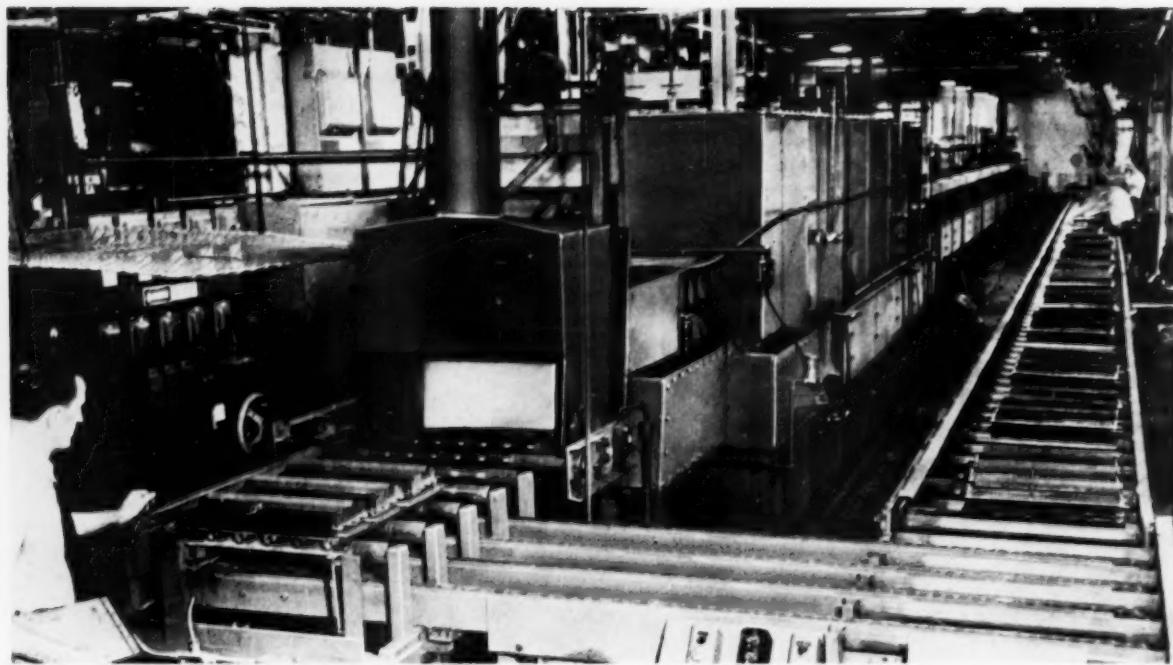
For Cupola Type Furnaces. For back slagging cupolas, the Norton **B** is CRYSTOLON slag hole blocks, as shown. For capping the notch and lining the slag chute in front slagging cupolas, CRYSTOLON bricks and cement are prescribed. This refractory material is engineered to give exceptionally long service life at temperatures up to 3050°F. It has great resistance to slag penetration and chemical attacks—and 5 to 15 times the resistance of ordinary fire clay to erosion and corrosion.



For Reverberatory Furnaces. The **B** for this reverberatory furnace is Norton CRYSTOLON refractory cement, engineered for maximum service life of this particular metal-melting job.



For Electric Furnaces. Furnace equipment of this type operates at lowest performance and maintenance costs when CRYSTOLON heating elements — Norton "Hot Rods" — are installed. They're the newest Norton **B**, engineered and prescribed for electric furnaces. They can be used to replace your present rods — and have proved their ability to deliver two to four times longer service life. Ask for our special booklet on CRYSTOLON "Hot Rods" for all applications.



G-E Furnaces for Low-cost, High-quality Heat-treating

A complete line of G-E furnaces provide precision heat-treating for a wide variety of industrial applications. These units reduce subsequent cleaning operations, greatly reduce inspection and rejects.

Features

Charges are heat-treated uniformly at exact, controllable temperatures. G-E atmosphere producers prevent decarburization or scale formation. Carefully designed cooling and quenching facilities enable uniform cooling of every part at the desired rate. In many cases, the complete cooling cycle is entirely

automatic, eliminating all uncertainty of the human element. Less maintenance is required with rugged heating units and sturdy furnace construction throughout.

Service Facilities

All furnaces are installed and tested under close supervision of skilled G-E heating engineers. G-E Service Shops near every industrial center are available day and night for repairing, reconditioning, or modernizing all furnace equipments.

Types of Furnaces and Bulletins Available

Bell, cylindrical (1200 F max)	GEA-1752
Bell, cylindrical (1400 F max)	Write for details
Bell, rectangular	Write for details
Belt conveyor	Write for details
Box, air-drawn	GEA-785
Box, air recirculation	Write for details
Box, with protective atmosphere (2000 F max)	GEA-3596
Box, with protective atmosphere (2500 F max)	GEC-982
Box, without protective atmosphere	Write for details
Box, with cooling chamber (2100 F max)	GEA-4066
Box, with cooling chamber (3100 F max)	GEA-4713
Box, porcelain enameling	Write for details
Car-bottom	GEA-4068
Catenary	Write for details
Continuous, porcelain-enameling	Write for details
Cylindrical, pit air-draw with fan (1250 F max)	Write for details
Cylindrical, pit with fan (1750 F max)	Write for details
Cylindrical, pit without fan	Write for details
Elevator	GEC-1236
Galvanizing	Write for details
Mesh-belt conveyor	GEA-4071

Pusher	Write for details
Rectangular pit	Write for details
Roller-hearth	GEA-4072
Rotary-hearth	GEA-4073
Salt-bath (1100 F max)	GEA-4074
Tempering baths (oil or salt)	Write for details
Tower	Write for details
Truck	Write for details
Wire-enameling	Write for details

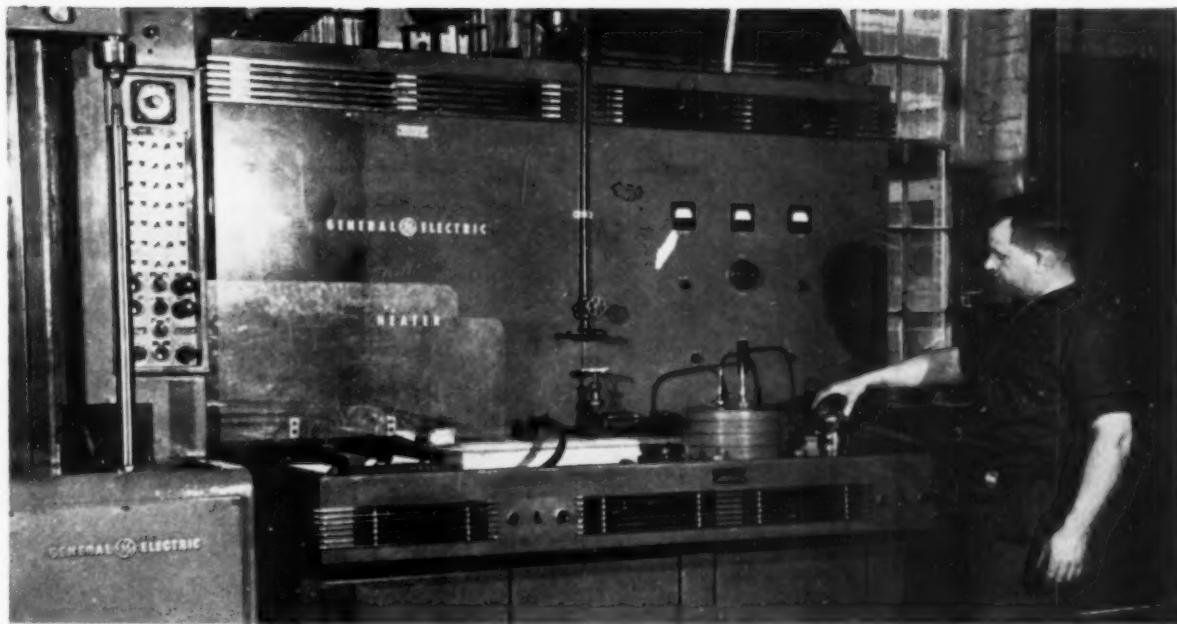
Atmosphere Equipment

Thermalene* producer	Write for details
Ammonia dissociator	GEA-4075
Atmosphere gas converter	GEA-2948
Dryer (activated alumina)	Write for details
Neutralene* producer (CO ₂ free and dry gas)	GEA-4707
Refrigerated gas cooler	GEA-4924
Sulphur remover	GEA-4923

Control Equipment

ON and OFF control	Write for details
Reactrol* control	GEC-1243

*Registered trade-mark of General Electric Company.



G-E Induction Heaters Improve Product Quality, Reduce Over-all Costs, Increase Production

Most modern production layouts call for equipment that fits into straight-line production operations. Space-saving induction heaters are easy to install at any point in the production line where they will provide automatically controlled heat exactly where it is needed. Each part is heated rapidly, resulting in uninterrupted production with a minimum of operator training. Work-in-process, kept at high levels by batch-type heating, is minimized. Warm-up periods and waste heat are eliminated. These are only a few of the factors which make versatile, induction heating

equipment a valuable production tool for today's manufacturing.

Electronic-type Induction Heaters

These units are used for annealing, soldering, brazing, surface hardening, and many miscellaneous applications — particularly when selective heating is desired. This type of heater is available in output ratings of 5, 10, 20, and 50 kw at 530 kilocycles with a complete line of accessories. Special heating machines or fixtures can be designed and built to individual requirements.

Motor-generator-type Induction-heating Equipments

These are available in ratings from 50 to 1250 kw with nominal frequencies of 1000, 3000, and 10,000 cycles. Applications are similar to those for electronic-type induction heaters, but usually the motor-generator-type equipments are used for larger parts. Complete equipments consist of a motor-generator set, motor control, generator control, capacitors, and complete accessories. Special heating machines or fixtures can be designed and built to individual requirements.

Bulletins on Induction-heating Equipment

Forging with induction heat.....	GEA-5983	20-kw electronic-type induction heater.....	GEC-1250
Furnace and induction brazing.....	GEA-5889	50-kw electronic-type induction heater.....	GEC-921
Induction heating in industry.....	GEA-4945	Water economizing and tempering unit for electronic-type induction heaters.....	GEC-922
Equipment for induction heating.....	GEA-5679	Generator control panels for induction heating.....	GEA-4989
5-kw electronic-type induction heater.....	GEC-920		

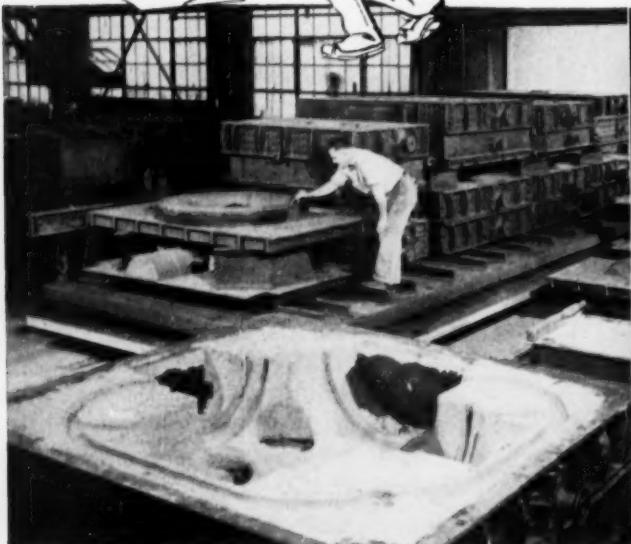
To obtain any of the bulletins listed on these pages, or for further information, contact your nearest G-E Apparatus Sales Office, or write to Section 640-389, General Electric Company, Schenectady 5, N. Y.

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GENERAL  **ELECTRIC**



These are the
working with the
to make your



AT LEBANON there are electric furnaces capable of melting up to 8500 pounds—induction furnaces with 2000-pound maximum capacities. Here, too, special Swiss* molding and production processes are combined with the finest in American methods and procedures. The CENTRI-DIE* process for making centrifugal castings in permanent molds—a process

introduced in this country by Lebanon—provides the highest quality castings for difficult corrosion and heat resisting services. Pattern-making, core-making, heat-treating, finishing and cleaning complete the picture of equipment that produces Lebanon CIRCLE ® castings.

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CARBON, SPECIAL ALLOY AND STAINLESS STEEL CASTINGS
LEBANON
STEEL FOUNDRY LEBANON —
PENNSYLVANIA

right men

right equipment

STEEL CASTINGS



foundrymen add immeasurably to the high quality of CIRCLE® engineered products. These workers are craftsmen in every sense of the word, men trained and highly skilled, men dedicated to doing all they can to make your castings *right*.

If the pictures on these pages could talk they'd say, "Here's where equipment and craftsmen make

Lebanon CIRCLE® castings to a *high standard—not to a price!*" We believe sincerely that there is no economy in buying just by price . . . it is far better to buy the best product at a reasonable cost.

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*Special processes acquired from George Fischer, Ltd., of Switzerland. Lebanon Steel Foundry was also the original licensee for the centrifugal casting process developed by Firth-Vickers Stainless Steels, Ltd., Sheffield, England.

Lebanon Steel Foundry
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Please send me one of your new Lebanon Slide Charts.

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This handy slide chart gives you the nominal analyses, various designations, minimum mechanical properties and heat treatment for 19 Lebanon carbon and low alloy grades and 17 stainless and corrosion-resistant grades. Send coupon today . . .



The Big Trend in Metalworking...

MOVE the metal ...it's cheaper than

HOW NEW METHODS SAVE BIG SUMS

A. Parts are produced primarily by forcing metal into the desired shape rather than by "removing" or "machining" it. It is far faster... saves tremendously in time and labor.

B. The amount of metal in the initial slug, shot, billet, sheet, etc., is only slightly more than the total amount in the finished piece. Thus scrap and machining are held to an absolute minimum.

Metalworking plants casting about for ways to reduce production costs are turning more and more to the newer methods of forging, drawing and extruding in which metal is being "pushed around" rather than "removed." These processes basically are the hot extrusion of alloy steel, cold "pressure" forging of aluminum, cold extrusion of steel, and high pressure closed die extruding of aluminum and other non-ferrous alloys. Also falling within this category



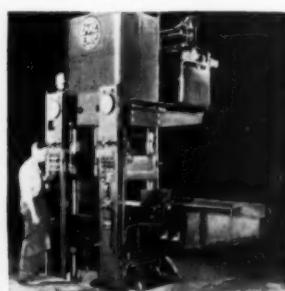
Closed die extruding
of heated aluminum reduced
production time 99%.



Cold steel
extrusion reduced
scrap 43%.



Hot alloy steel extrusion
is now an
established art



Metal powder parts
are often produced with no
machining.

● *New and improved production techniques save millions...arouse widespread interest*

1. Actual parts production is cut from hours in typical cases to minutes or even seconds.
2. Pieces generally have superior finish and improved physicals including grain structure.
3. Tolerances and uniformity equal or better those of older methods.
4. Scrap is greatly reduced and in many cases practically eliminated.
5. Unit costs go way down.

MOVING it!

are somewhat older though greatly changed and improved methods for the extrusion of aluminum, hot forging of ferrous metals, powder metallurgy, deep drawing of sheet and die casting. The most recent developments involve variations and combinations of the above applied to many products and materials. Our engineers are in close daily contact with these developments. They'll be glad to help apply any of them to your production. Call or write us.

LAKE ERIE HYDRAULIC PRESSES

LAKE ERIE ENGINEERING CORP

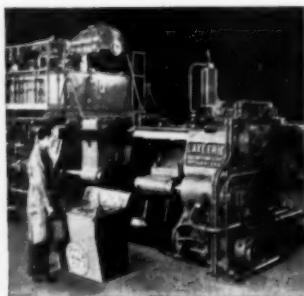
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HYDRAULIC PRESSES • DIE CASTING MACHINES
ROLLING MILL AUXILIARY EQUIPMENT



New developments in steel forging have greatly expanded its application.



Non-ferrous extrusion installations now embrace titanium, magnesium and newer metals.



Production rates of die cast aluminum and zinc parts have been upped 20% to 30%.

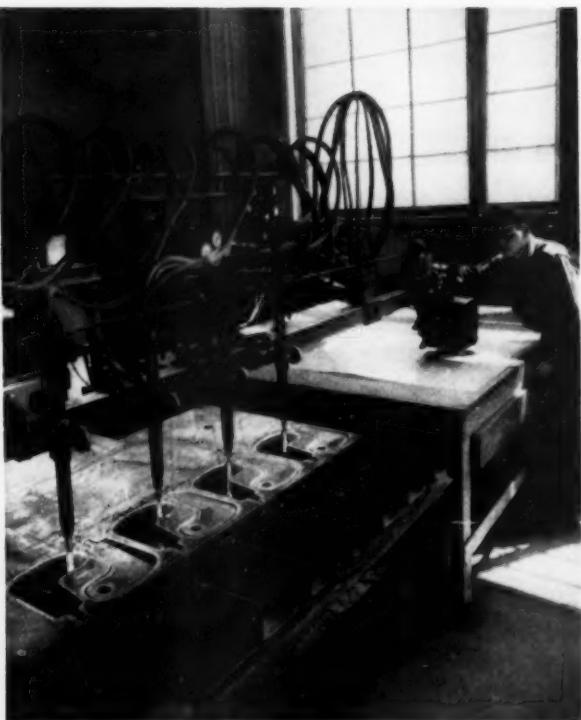
PACKAGED INSTALLATIONS

A new service by Lake Erie which enables you to order an integrated installation ...including production equipment, tooling auxiliary equipment and advisory service ...from a single source thereby saving time, money and trouble.

LAKE ERIE •

Delivering industrial "breath"—Oxygen supply and servicing is as important as its unit price and purity. Airco customers get a dependable, flexible supply service from a network of 70 producing plants situated strategically throughout the country. Delivery, by bulk truck (far right), in cylinders, or by direct pipeline is quick and dependable. Right: valve opening ceremony last year at the new Airco liquid oxygen plant, Butler, Pa. These pipelines deliver oxygen to Armco Steel and Pultman Standard steel plants.

New welding process speeds production—Among industry's newest production tools is the Aircomatic® process. The method greatly increases the speed with which good welds can be made in a wide variety of metals and alloys, including "problem" materials like aluminum and stainless steel. This photograph shows the inert-gas-shielded metal arc of an automatic Aircomatic head welding truck-trailer dolly wheels from press-stamped SAE 1020 steel at Youngstown Steel Car Corp., Niles, Ohio. Oxygen plays an important part here as an additive to the shielding gas.



Most dramatic use of oxygen—Flame cutting is perhaps the most spectacular industrial application of oxygen...as useful as it is striking. The oxygen-acetylene flame used generates 6300°F-heat. This temperature permits cutting metal thicknesses ranging from sheet to heavy ingots. Here, an operator at Brown-Wales Co., New England steel warehousing firm, cuts steel plate with an Oxygraph equipped with Electronic Tracer, one of the Airco precision machines that has brought flame cutting to a peak of usefulness.





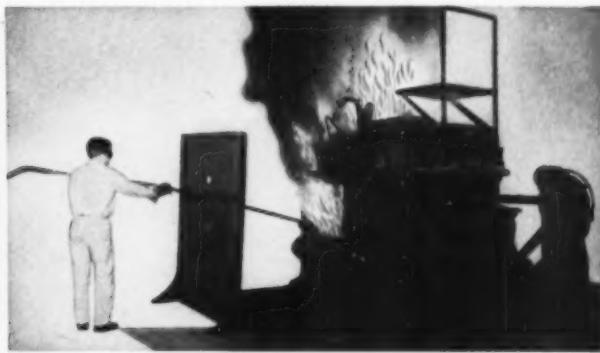
Airco Oxygen Tent for Industry

The vital importance of oxygen to industry is relatively new. Forty years ago, the market for oxygen in cutting and welding and allied uses was virtually nonexistent. The rapid growth of industrial oxygen consumption has been nourished by three conditions: an expanding economy, the wider use of any effective

product in healthy conditions of economic expansion, and the development of new and improved tools and techniques whose effectiveness depends on oxygen. For details of these and other applications of Airco products, write for a sample copy of the magazine, "Airco in the News."



Oxygen in the glass industry—Insatiable demand for light bulbs, electronic tubes, and similar glass components has brought modern mass production methods to the old art of the glass blower. This "sealing-in" machine at Sylvania Electric Products, Inc. seals bulbs and mounts into 150-watt inside frosted incandescent lamps at a 1500-per-hour rate. A mixture of oxygen-enriched air and natural gas provides the right flame shape and temperature in the jets that soften the throats of the bulbs prior to sealing.



Needling steel for production economy—Oxygen has replaced iron ore as an oxidizing agent in most steel mills with electric furnaces. Here at Mid-Continent Steel Castings, Shreveport, La., a long pipe injects the oxygen directly into the molten steel. Advantages of this Airco-pioneered process are savings in time, power, furnace electrodes and valuable alloy elements. Other oxygen applications include flame cutting of heavy scrap, scarfing, flame cleaning, oxyacetylene welding, dehydrating, hard-facing, and gas hot topping of ingots.

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Represented Internationally by Airco Company International

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AJAX Induction
Melting Furnaces
are Versatile!



SOME APPLICATIONS

Die Castings
Sand Castings
Permanent Mold Castings
Scrap Recovery
Billets for Rolling and Extrusion
Galvanizing and Aluminizing of Steel
Continuous Casting of Metals

AJAX-TAMA-WYATT Low Frequency Induction Furnaces are made in a wide range of sizes, from 20 to 1000 KW, to meet demand for large volume or small special lots. They are adapted to the full range of non-ferrous metals and alloys. Their use insures faster production, uniform quality, less maintenance and lower operating cost.

Rejects are reduced. For special applications, an Automatic Electromagnetic Pump allows continuous feeding of molten metal into the molds as they move past. Hand ladling is eliminated. Temperature is also automatically controlled and there is no chance of overheating the bath at any time during the melting cycle.

WRITE FOR FURTHER INFORMATION

AJAX
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INDUCTION MELTING FURNACE**

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AJAX ELECTRIC CO., INC., The Ajax Halogen Electric Salt Bath Furnace
AJAX ELECTRIC FURNACE CORP., Ajay Wyatt Induction Furnaces for Melting



ALCOA SECTION

Page 1 of 4 Pages

Design facts you should know about ALCOA® Aluminum Forgings

Improved equipment and production techniques mean aluminum forgings now compete with other metals and fabricating processes

View of 15,000-ton hydraulic forging press operated by Alcoa's Cleveland Works.

Not only has this press contributed to research on still heavier presses, it has permitted significant design improvements by way of reducing "small pieces" construction.

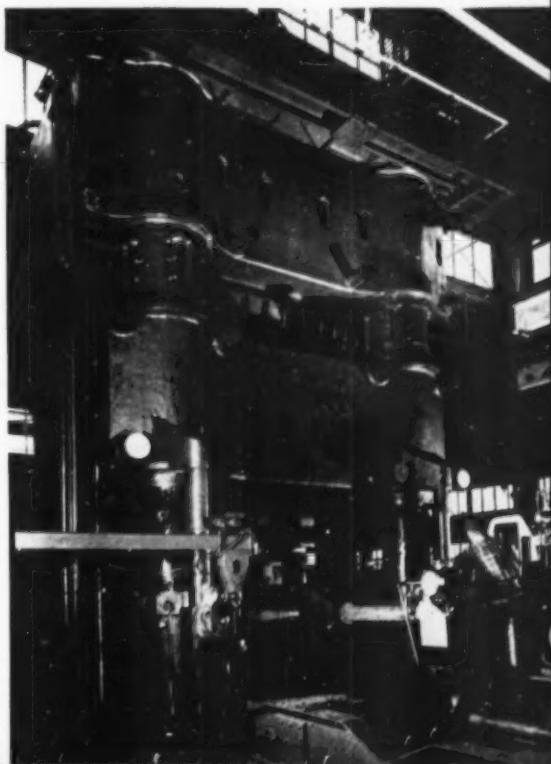
In the period between 1946 and 1949, production of aluminum forgings increased over 100 per cent at Alcoa alone. With the addition of the large 15,000-ton hydraulic press in the Cleveland Works, along with other equipment since put into operation, production has increased still further. These improved facilities mean higher output of better quality aluminum forgings at a cost that makes them competitive with other metals and other fabricating processes.

What about the future? We suspect you have already heard of the giant 35,000 and 50,000-ton presses now being constructed for our Cleveland Works—expected to be in operation this year—and are aware of the tremendous new design possibilities facilities such as these will provide.

Parts will be still bigger, will have thinner web sections, less draft, closer tolerances, better dimensional stability, to say nothing of being more complicated.

What's more, an ever-increasing share of the aluminum forging output from now on will be commercial, not military. In short, automotive, electrical appliance, tool, and engine designers, in fact, designers in all of industry—taking hints from the military—are turning to aluminum forgings for better, stronger, lighter, yet lower cost parts.

A glance through the next few pages will show you reasons why.

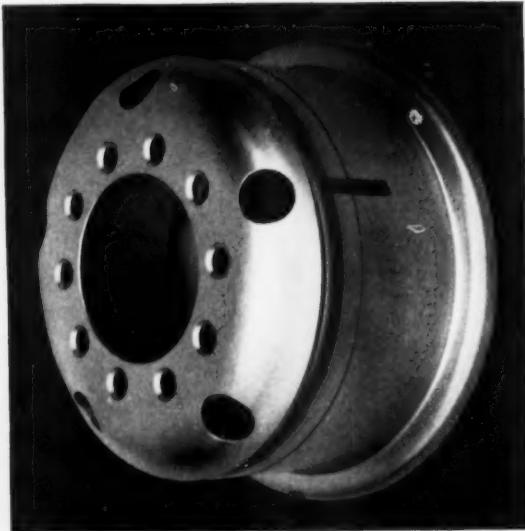




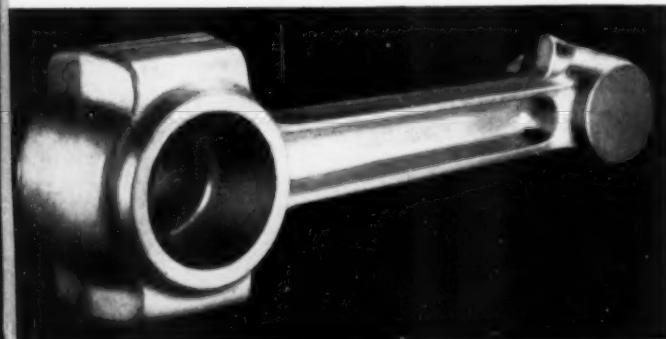
ALCOA SECTION

Page 2 of 4 Pages

These people use **ALCOA** Aluminum Forgings



FORGED WHEELS—Weighing 48 pounds, 40 less than its steel counterpart, this Alcoa Forged Aluminum Disc Wheel for trucks and buses is proving its superiority by reducing unsprung weight, allowing larger payloads. Machined from an aluminum forging, these wheels literally are rounder which means less vibration, less maintenance.



Aluminum forgings possess all the inherent characteristics of aluminum, such as light weight, corrosion resistance, and good machinability; and combine with these advantages great strength, comparable to that of structural steel.

The result: high strength-weight ratios—excellent for such applications as aircraft, truck and bus where range, speed and payload depend on light body weight, yet sufficient strength to support that load.

Weighing about one-third less than structural steel, aluminum forgings help reduce operator fatigue when they are used in parts frequently carried, lifted or handled. Hand power tools are a good example. With their lower elastic modulus, aluminum forgings have several times the impact-absorbing capacity of mild steel.

Other features make aluminum forgings stand out. For example, they are easily machined, often at speeds of 1000 fpm. But, their smooth, bright surfaces often make subsequent machining unnecessary. What's more, inspection costs are less. Part dimensions are uniform, keeping scrap loss to a minimum.



CUTTER DISK—An Alcoa Forged Cutter Disk to be used on a concrete surfacing machine. Because of their great strength, Alcoa Forgings are perfect for highly stressed moving parts. Further, their light weight means less driving horsepower. Sturdy, these forgings can stand severe abuse in emergencies, provide dependable service under normal load, all with less maintenance.

CONNECTING RODS—Forged aluminum connecting rods not only are strong, but, being light, more of the horsepower developed by the engine can be directed toward driving the outside load rather than the engine's own parts. Alcoa Forged Pistons are in use today in diesel engines driving trucks, buses and railroad locomotives.

Alloy selection

It is possible to produce aluminum forgings with tensile strengths varying between 15,000 and 75,000 psi, depending, of course, on the alloy selected. But you can save money by utilizing that alloy which most nearly matches your strength requirements. Too, each alloy has certain other characteristics that may actually be more significant than strength.

For example, alloy 2S, commercially pure aluminum, has high electrical conductivity and good corrosion resistance; and, because of its shiny appearance, is often used for decorative effects. Or 14S, the general-pur-

pose forging alloy, also has good corrosion resistance coupled with high strength and excellent machinability. Alloy 32S, with its low coefficient of thermal expansion, is highly suitable for diesel engine pistons. Alloy 61S has very good welding and brazing qualities, plus high resistance to corrosion.

But, where very high strength is called for, such as in aircraft or structural installations, alloy 75S is frequently used. Or 76S, with its excellent fatigue strength and high degree of hardness, is perfect for highly stressed parts, such as propellers.

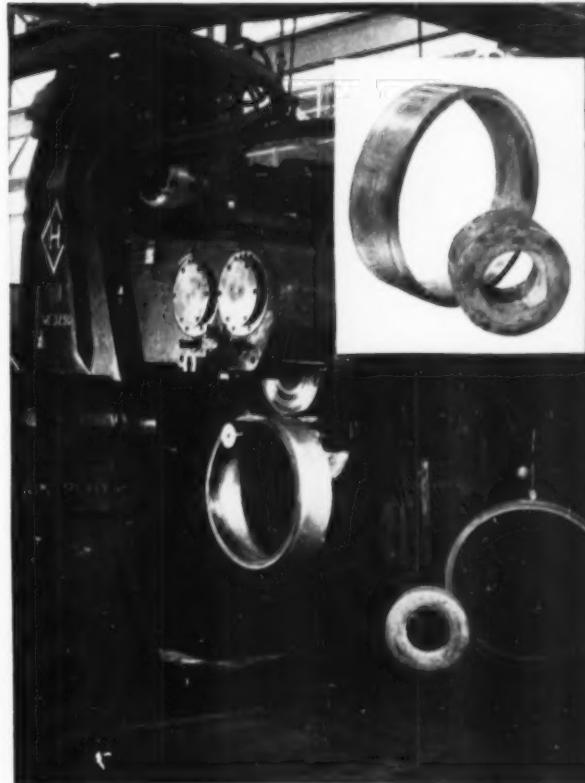
what about cost?

Cost of the piece as it comes from the forging press is only half of the aluminum forging cost story. To keep this half low, Alcoa is constantly adding new equipment and improving the old. For example, the largest facilities in the world for sinking aluminum dies will soon be in operation at the Cleveland Works.

And, a new machine for roll forming aluminum rings in sizes up to 40 inches O.D. and 20 inches wide has been added. The ring roller, as it is called, is capable of turning out rings to closer tolerances, with better surface finishes than any previous methods. Then, of course, there's the 15,000-ton press. These new facilities spell more faithful reproduction of design, fewer rejections, faster inspection, hence, lower as-forged costs.

The other half of the cost picture concerns cost per finished piece. As forgings, shapes can be made more complete when they come from the press. The result: design can be greatly simplified, improving quality, and keeping subsequent machining, assembling, and finishing operations to a minimum.

So, if you have hesitated to make your product as an aluminum forging because of cost, take another, longer look . . . today.



New ring roller now in production at Alcoa's Cleveland Works. This machine is capable of producing rings up to 40 inches O.D. and 20 inches wide with closer tolerances, better surface finish, and at lower cost than previous methods.



ALCOA SECTION
Page 3 of 4 Pages



Want more information?

If you would like to know more about what we at Alcoa have found out about this business of forging aluminum, we'd be glad to send you a cloth-bound book, *Designing for Alcoa Forgings*, that is sure to answer many of your questions.

Write on your company letterhead, telling us your job function, to ALUMINUM COMPANY OF AMERICA, 1989-F Alcoa Building, Pittsburgh 19, Pennsylvania.

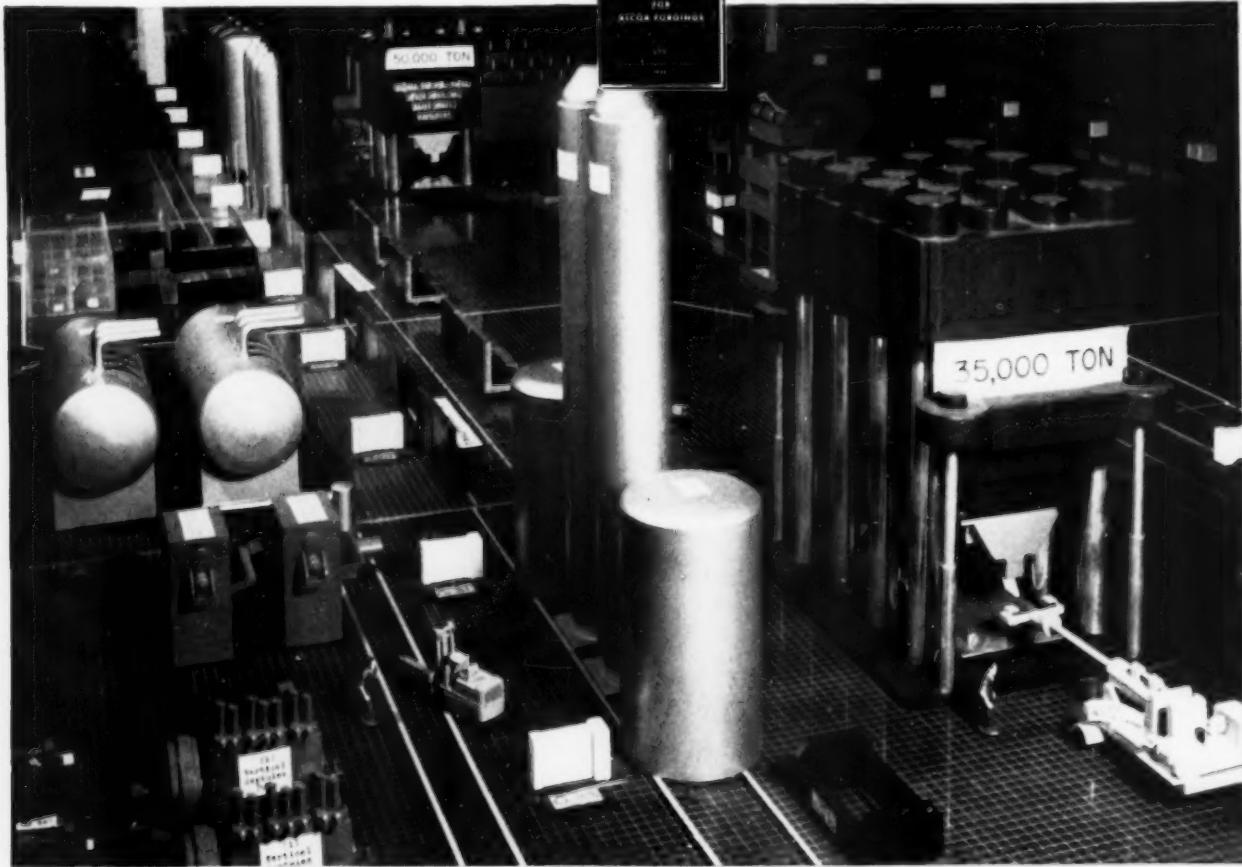
In this book, you'll find detailed facts on why you should keep radii full and fillets generous—why it's important not to blend radii unless it's absolutely essential—how sharp corners can cause the diesinker troubles, possibly lessen die life.

Too, the book goes into great detail on draft angles—for most shapes, 7° is standard, but this can vary downward according to the size and shape of the part as well as the alloy employed. A whole section is devoted to web and rib thickness, their design and

relationship to cost. For example, for thin webs, dimensional tolerances are hard to maintain because the web cools more quickly and shrinks faster than other parts of the forging.

It tells how, by taking advantage of metal flow, maximum mechanical properties can be obtained at critically stressed sections. Further, the parting line is discussed in relation to part design, cost and quality.

All these facts and others not mentioned are important to you. Write for your book soon. And, if you have some question you'd like to discuss now, there's an Alcoa sales engineer near you. His office is listed under "Aluminum" in your classified telephone directory. Don't hesitate to call him—to use his time and knowledge freely.



Scale models of the 35,000 and 50,000-ton presses expected to be in operation sometime this year. Building that will house the two presses will be more than 100 feet high over the press bay, will cover about 12 acres of land—more area than six full-sized football fields.

Warplis

PRECISION GROUND

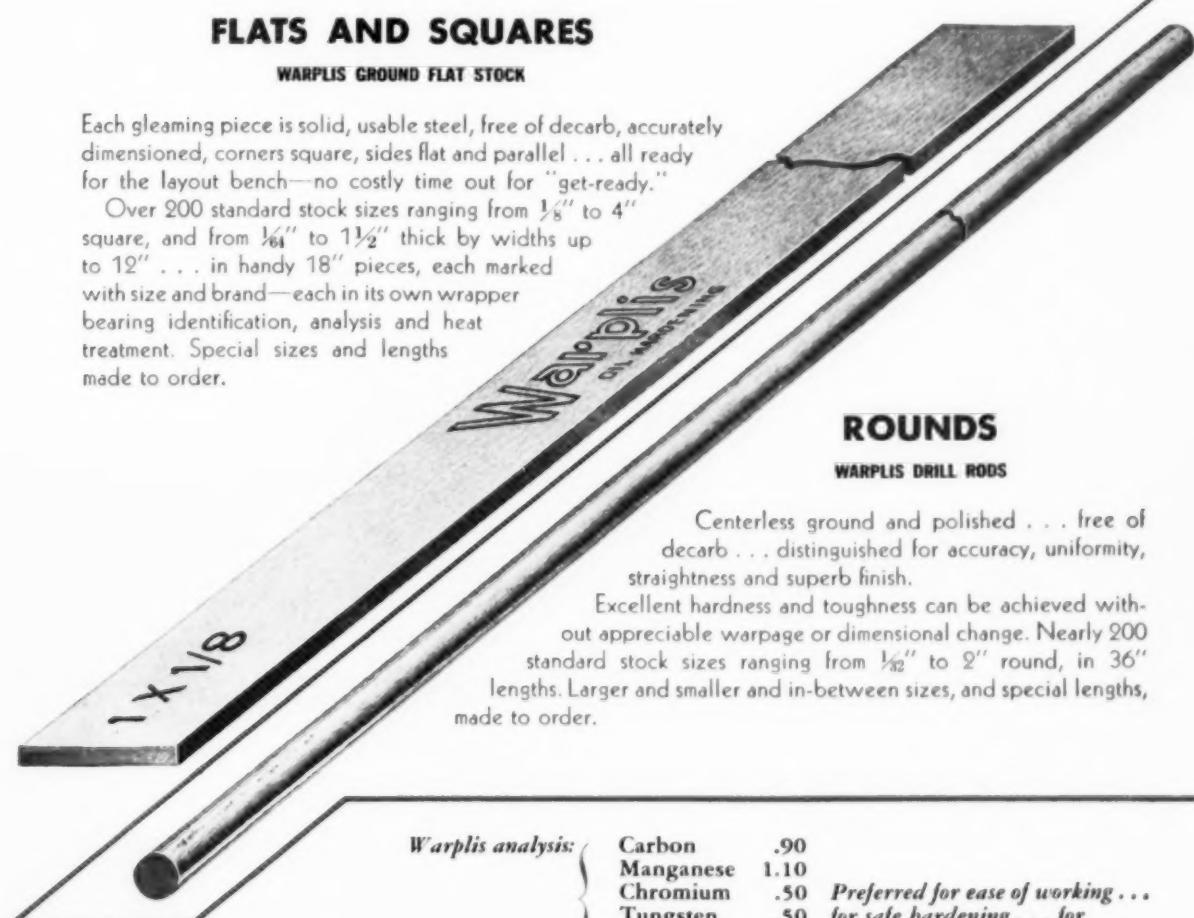
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Each gleaming piece is solid, usable steel, free of decarb, accurately dimensioned, corners square, sides flat and parallel . . . all ready for the layout bench—no costly time out for "get-ready."

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Excellent hardness and toughness can be achieved without appreciable warpage or dimensional change. Nearly 200 standard stock sizes ranging from $\frac{1}{32}$ " to 2" round, in 36" lengths. Larger and smaller and in-between sizes, and special lengths, made to order.

Warplis analysis:

Carbon	.90
Manganese	1.10
Chromium	.50
Tungsten	.50
Vanadium	.15

Preferred for ease of working . . . for safe hardening . . . for fine performance.

Procedures may be simplified . . . time and money saved . . . by standardizing on these companion products of Tiffany-like quality for all tool and die requirements. From fine steel distributors everywhere. Size and price folders, and Warplis Notes on Hardening pamphlet, on request.

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Reliance water hardening flat and square drill rods
High Speed drill rods

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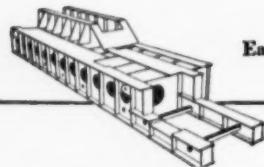


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Here you can get them. Here men know how to work with metals. How to cut, shape, weld, heat-treat and machine the most complex assemblies. They have learned by producing thousands of varied weldments for machinery builders and other industrial users . . . by building rolling mills and special machinery bearing the Continental name . . . by wartime production of welded tank components and armor. They have tools—the steel fabricating bay is shown—to cut costs. They work under scientific quality control—from production of needed castings to finished assembly. Call in a Continental engineer to help you find better, more economical weldments for your production needs.



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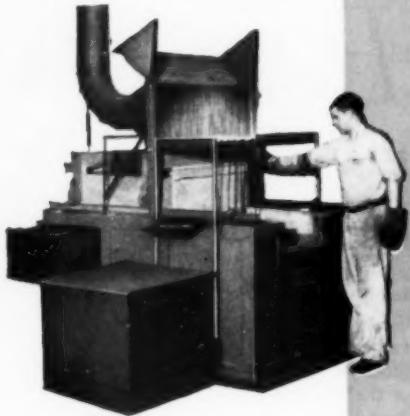
Complete protection of work against pitting, scaling, carburizing or decarburizing . . . Heating cycles 4 to 6 times faster . . . Low operating and maintenance costs . . . First cost of equipment materially less.

ALUMINUM HEAT TREATING

More production in less time . . . Faster, more uniform heating . . . Simplified quenching . . . Minimum warpage . . . Real protection to product by molten salt . . . Clean . . . No skilled labor needed.

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Large production in less space from smaller equipment . . . Minimum distortion . . . Higher and more uniform surface hardness of the finished product assures superior impact fatigue life.



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★ Note these typical advantages

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Work can be immersed in batches for maximum speed and economy . . . All joints brazed simultaneously in seconds . . . No decarburization of steel assemblies . . . No cooling chamber needed . . . Can be simply combined with carburizing or hardening.

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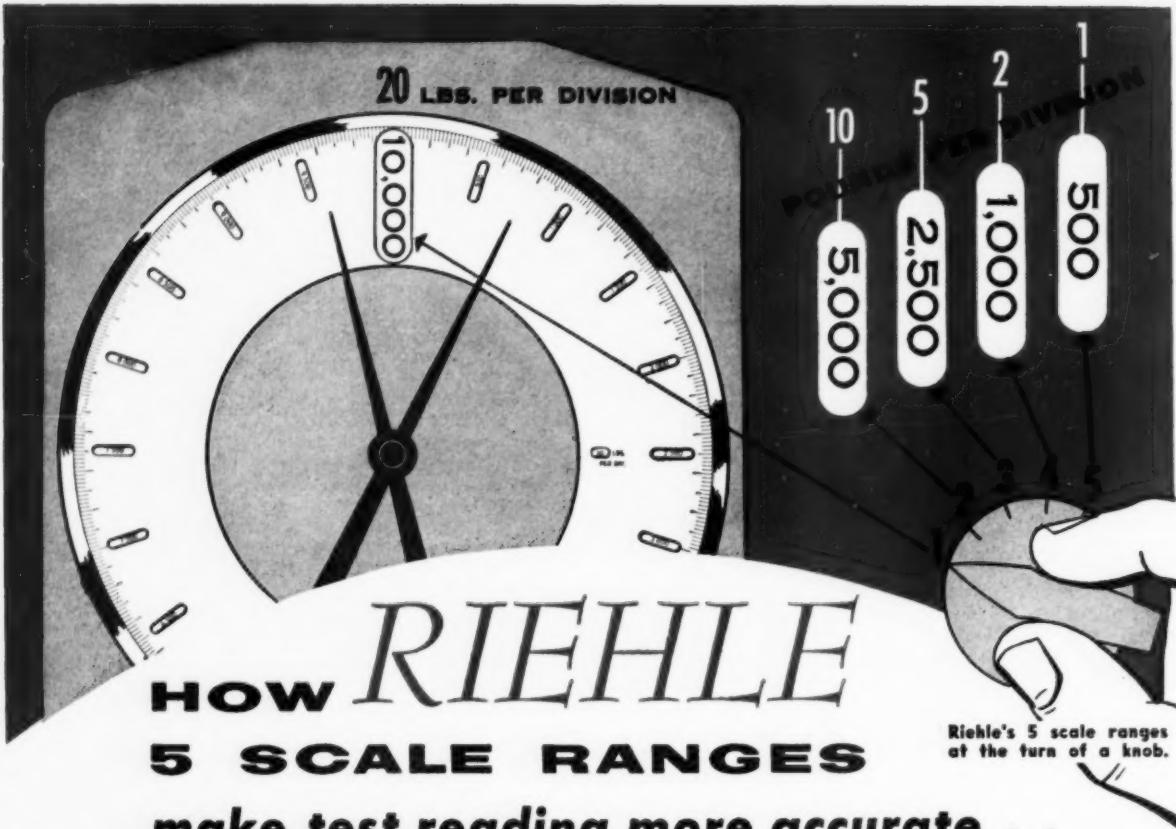


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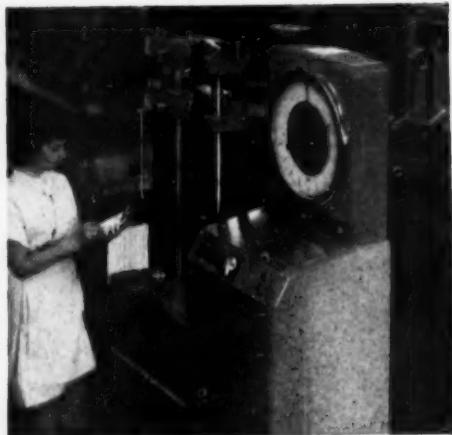




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Low loading table and gripping head make it easy to place specimens in a Riehle Universal Testing Machine. Its streamlined design enhances the appearance of modern testing laboratories.

There's no chance for mis-reading when you're using a Riehle Pendomatic Universal Testing Machine.

On beginning a test, the operator sets Riehle's selector knob to the logical scale range. Automatically the corresponding pound load figures appear on the indicator dial. Riehle's 5-range system allows most exact interpolation by providing the fewest number of pounds per dial division. For example, when using range 5 on a 10,000 pound Riehle Pendomatic Universal, each division represents only 1 pound. This feature assures greater accuracy in reading. Also it lessens the chance for error if the operator happens to read the dial from a slight angle.

This 5 scale range dial is a standard feature at no extra cost, on all Riehle Pendomatic Universal Testing Machines.

Accurate to $\frac{1}{2}\%$, a Richle Tester is mechanically simple, rugged and foolproof.

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• NAME AND TITLE



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302. Alloy Castings

Data folders on two types of alloy steel castings. Composition, properties, hardening, heat treatments, uses. *Unitcast*

303. Alloy Steel

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312. Aluminum Strip

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52-page Technical Bulletin T-36, "Methods for Chemical Analysis of Nickel and High-Nickel Alloys". *International Nickel*

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16-page booklet on aluminum products for architectural use, aluminum structural shapes, embossed finishes on aluminum. *Reynolds Metals*

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316. Atmosphere Furnace

Bulletin on controlled atmosphere furnace. *Industrial Heating Equipment*

317. Atmosphere Furnaces

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mation on inert gas generators and data on costs. *C. M. Kemp Mfg.*

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Bulletin on properties, grades, applications of carbon and graphite brick for handling corrosive chemicals and molten metals. *National Carbon*

339. Carbon Control

Technical report on instrument for control of carbon potential of furnace atmospheres. *Lindberg Eng'g*

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Data folder on Aerocarb E and W water-soluble compounds for liquid carburizing. Case depth vs. time curves. Percent carbon and nitrogen penetration curves. *American Cyanamid*

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Bulletin on carburizers for pack carburizing. *Park Chemical*

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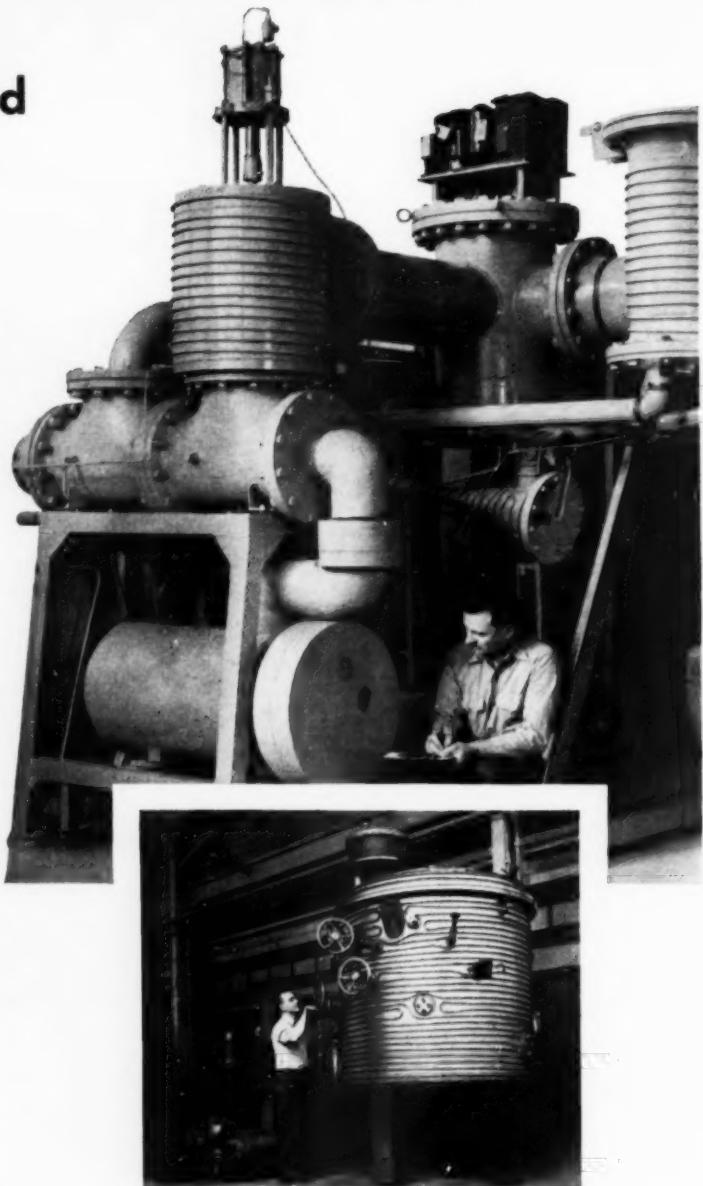
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HEVI DUTY BOX TYPE FURNACE

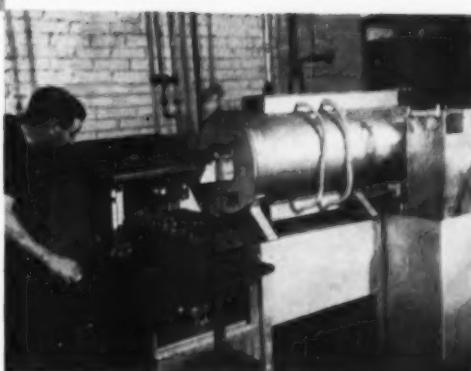
Hardening piston rings at 1850° F. is one exacting use of this furnace. Hevi Duty design and construction assures uniform and fast heating with low maintenance costs in electric furnaces for many applications.

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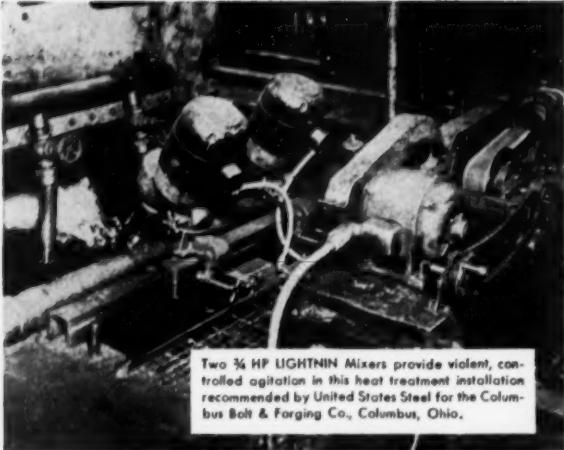
This modern production tool will either carburize, nitride, dry cyanide, or bright harden up to 150 pounds of work per hour. The work passes through the furnace and drops directly into the oil quench. Results are clean, uniformly treated parts with minimum distortion. Bulletin HD-850.



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Heat Treating Furnaces...Electric Exclusively
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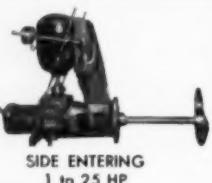
Two 3/4 HP LIGHTNIN Mixers provide violent, controlled agitation in this heat treatment installation recommended by United States Steel for the Columbus Bolt & Forging Co., Columbus, Ohio.

LIGHTNIN MIXERS improve quench methods ... help increase hardness depth up to 50% or more

Violent agitation of the quench bath can help you get steel of uniform hardness and microstructure with less distortion, assuring fewer rejects, minimum retreating. Tests show Brinell hardness can be increased up to 50% or more.

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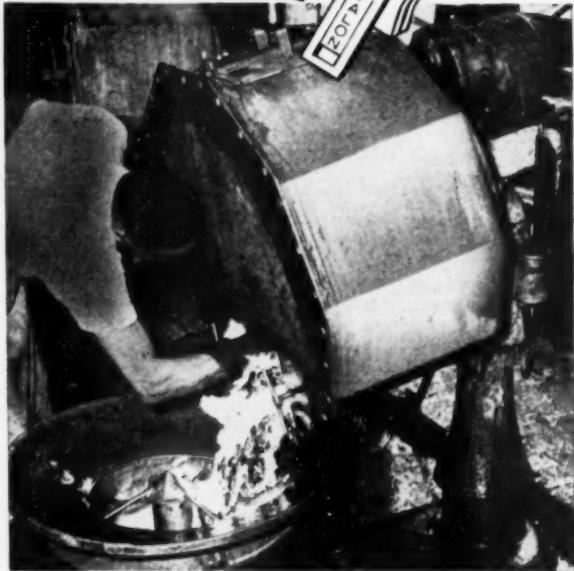


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Booklet on how brushes are used for cleaning welds, stainless sheets, hot cast iron, automotive parts, brass fixtures. *Pittsburgh Plate Glass, Brush Div.*

515. Meehanite

24-page bulletin on "Meehanite Castings Build Better Machine Tools". *Meehanite Metal Corp.*

516. Melting Furnaces

Catalog on Heroult electric melting furnaces. Types, sizes, capacities, ratings. *American Bridge*

517. Metal Cutting

64-page catalog No. 29 gives prices and describes complete line of rotary files, burrs, metalworking saws and other products. *Martindale Electric*

518. Metal Treating

32-page booklet includes soaking pits, heating furnaces, heat treating furnaces atmospheric equipment, quenching equipment. *Surface Combustion Corp.*

519. Metallograph

Bulletin E-29 on bright-field equipment for visual observation and photography. *Bausch & Lomb*

520. Metallurgical Apparatus

200-page catalog of metallurgical apparatus: cutters, grinders, mounting presses, polishers, metallographs, microscopes, cameras, testing machines, analytical apparatus, spectrographs, furnaces, accessories and supplies. *Buehler, Ltd.*

521. Metallurgical Products

Chart of typical chemical analysis and commercial uses of zirconium oxides, silicates, soluble salts, metallurgical and foundry alloys. *Titanium Alloy Mfg.*

522. Micropolishing

10-page brochure on units for polishing coils, blanks and sheets. *Murray-Way*

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Catalog on metallograph and several models of microscopes. *United Scientific*

524. Microscopes

8-page bulletin on several models of metallurgical microscopes. *American Optical*

525. Microscopes

Catalog Micro 8211 on heating microscope for study of melting behavior. *Leitz*

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Bulletin on how centrifugal castings of bronzes, nickel alloys and aluminum alloys are made. *Shenango-Penn*

530. Nonferrous Metals

"Metal of the Month" letters include market trends, statistics, helpful data. *Belmont Smelting & Refining*

531. Nonflammable Rust Preventive

Bulletin on rust preventive compound which is water soluble, nontoxic and nonflammable. *Production Specialties*

532. Oil Tempering

Bulletin on oil bath electric tempering furnaces. *Hevi-Duty*

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Data on pH meter. *Analytical Measurements*

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536. Photomicrography

Catalog E-210 on sliding base, high or low power photomicrographic equipment. *Bausch & Lomb*

537. Pickling

80-page book "Efficient Pickling" covers all variables of process. Many charts and tables. *American Chemical Paint*

538. Pickling Baskets

12-page bulletin on mechanical picklers, crates, baskets, chain and accessories. *Youngstown Welding & Eng'g*

539. Porous Chromium

12-page bulletin on hard, porous chromium coating for cylinder bores and bearing surfaces. *Van der Horst*

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168-page catalog, B-44, on bronze and ferrous alloys. Engineering data and information including design data, load capacities, specific properties, assembly procedure. *Amplex Div.*

541. Powder Metallurgy

6-page bulletin gives recommended design procedures on powder metal parts from ferrous and nonferrous metals. *American Sintered Alloys*

542. Powdered Metals

Booklet tells how things are made of powdered metals, applications and future possibilities. *Stokes*

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Brochure on precision casting of high temperature alloys. Alloys used, design possibilities. *Microcast Div., Austenal*

544. Precision Casting

44-page Catalog 53 covers every stage of the investment casting process. *Alexander Saunders*

545. Precision Casting

Illustrated folder, "Cost Reduction Through Investment Casting," shows diversity of parts to which process applies. *Casting Engineers, Inc.*

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50-page booklet describes protective coatings. *Atlas Mineral Products*

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8-page booklet on applications and cost reductions in oil-quenching installations. *Sun Oil*

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554. Radiography

Booklet on quality control through X-ray inspection. *Industrial X-Ray*

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556. Rare Earths

8-page Progress Report Number 1, "Rare Earths in Iron and Steel Melting". *Molybdenum Corp.*

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Bulletin 100 on production tester for measuring electrical resistance. *Rubicon*

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Case histories, operating data and test results with NA22H retorts. *Blaw-Knox*

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Rhodium plating as replacement for usual plating metals. *Baker & Co.*

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8-page bulletin on rotary files and burrs. *Martindale Electric*

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72-page book on cleaning, preservation, and packaging of metals. Causes of corrosion. *E. F. Houghton*

568. Rustproofing

Data sheet on slightly alkaline compound NR-31 for rustproofing iron and steel. *Enthone*

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12-page bulletin B-40 describes continuous and batch descaling lines for removing oxide from steel, bronze, copper, stainless and titanium. *Drever*

570. Salt Baths

Bulletin GEA-4074 on salt-bath furnace for operation to 1100° F. *G.E.*

571. Salt Baths

75-page manual on salt baths for case hardening and heat treating. *DuPont*

(Continued on page A-32A)

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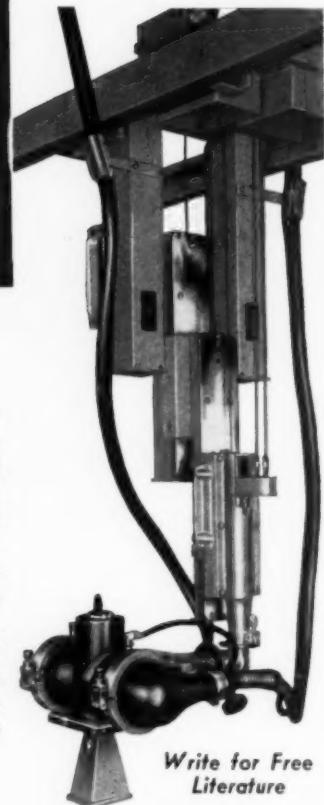


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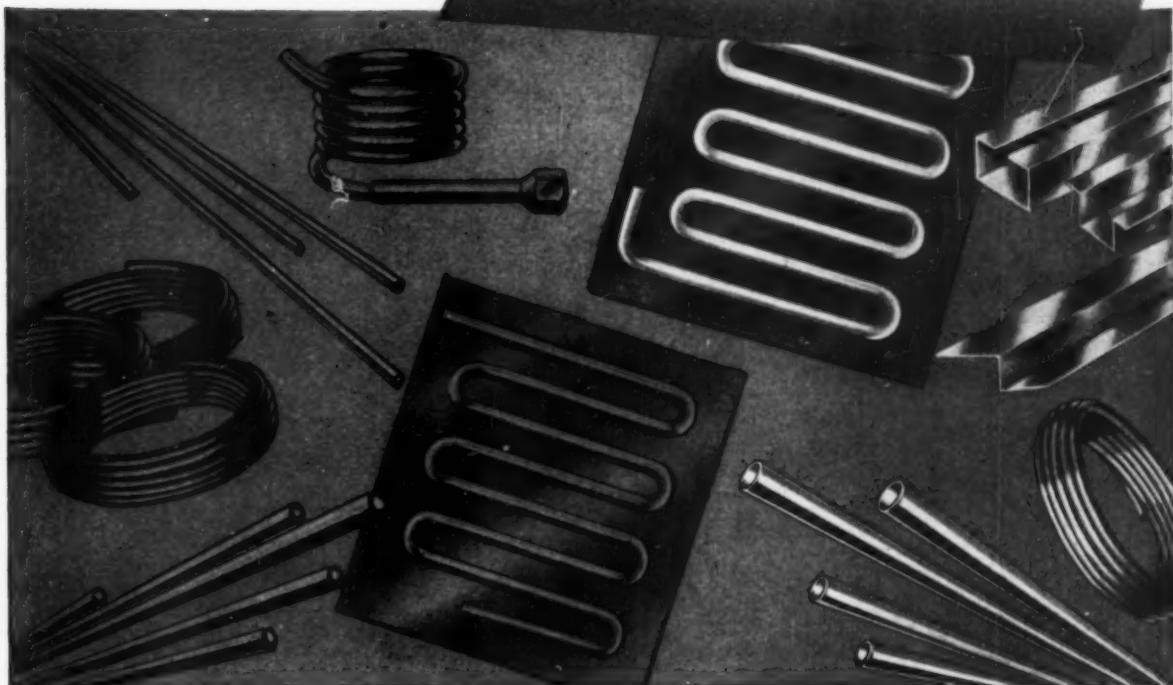


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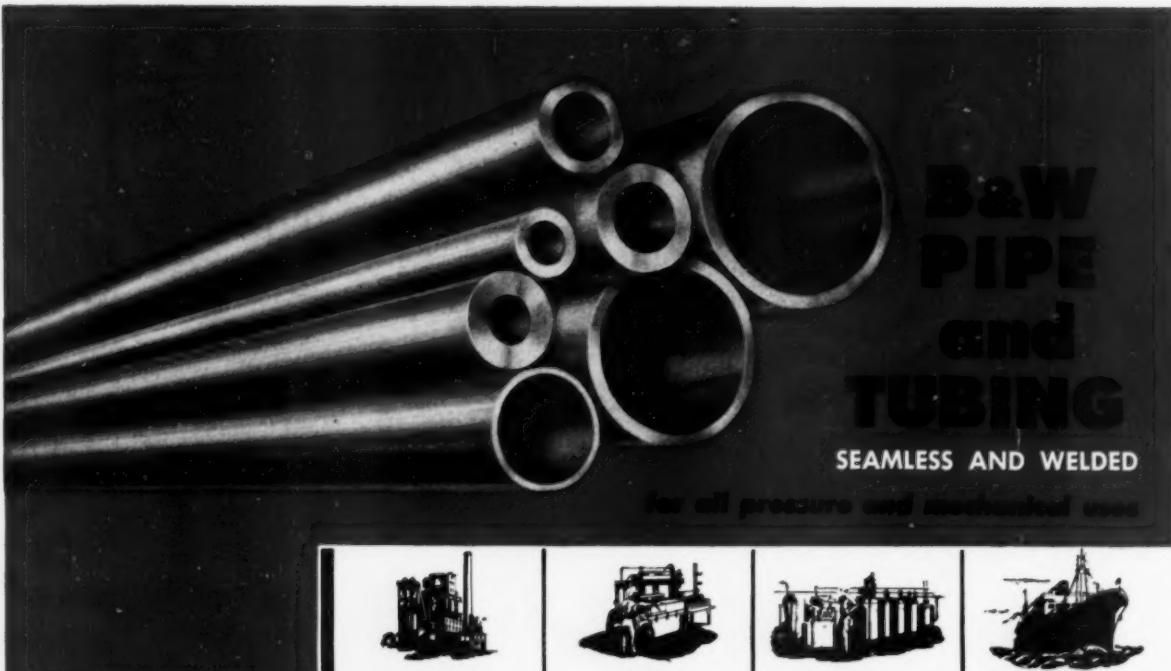
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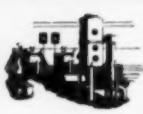
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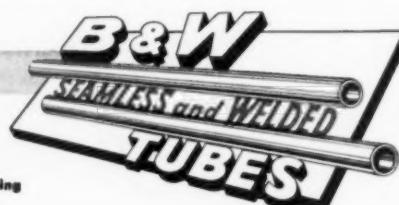
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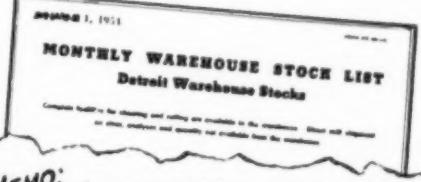
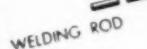
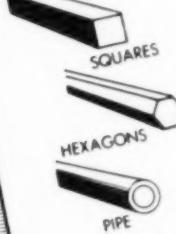
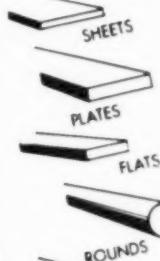
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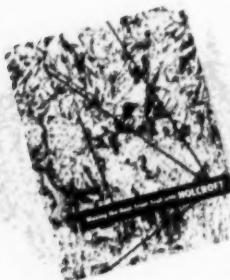
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(Continued from page A-29)

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72-page catalog, 116B, on operating principles and use of salt baths for 26 heat treating processes. *Ajax Electric*

573. Saws

Catalog of heavy-duty and high speed saws, band saws. *Armstrong-Blum*

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16-page book of design data and specifications on screw thread bushings of helically coiled wire, for aluminum, magnesium, iron, steel. *Heli-Coil Corp.*

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24-page book on handling sodium in the laboratory and plant. Application to de-scaling. *ethyl Corp.*

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6-page folder on use of a noncorrosive flux for soldering aluminum. Data on joint strength and ductility. *Insulation and Wires, Inc.*

580. Spectrographs

Catalog of spectrographic instruments—grating and prism spectrographs, vacuum spectrograph, precision varisource excitation units, recording and nonrecording microphotometers. *Jarrell-Ash*

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Spring steel catalog offers 785 sizes of hardened and tempered spring steels, and 133 cold rolled and bright annealed sizes in stock. *Sandvik Steel*

583. Stainless Applications

Bulletin on advantages of stainless in the chemical industry; units made, fabrication, design, alloys. *Crucible Steel*

584. Stainless Castings

Bulletin on advantages of corrosion-resistant castings. *Ohio Steel Foundry*

585. Stainless Castings

Bulletin on designs and alloys for stainless steel castings. *Waukesha*

586. Stainless Fasteners

96-page catalog of bolts, nuts, screws, washers, rivets, valves and fittings of stainless steel. *Allmetal Screw Products*

587. Stainless Steel

Selector gives machinability, physical and mechanical properties, corrosion resistance of various grades of stainless steel. *Crucible Steel*

588. Stainless Steel

Slide chart. Set top at a certain fabricating operation, bottom shows rating of each standard grade. On reverse side, heat treating and corrosion data are given. *Carpenter Steel*

589. Stainless Steel

Weekly stock lists for stainless plate give size, gage and type of stainless. *G. O. Carlson*

590. Stainless Tube

Bulletins on analysis and properties of seamless and welded stainless tubing. *Babcock & Wilcox*

591. Stainless Tubing

40-page catalog, section 20, on alloys used, fabrication and working, pickling process. Sections on welding, soldering, brazing, machinability, of heat resisting steels. *Superior Tube Co.*

592. Steel

256-page handbook lists sizes, weights, lengths, steels available, shapes. Data on mechanical properties, standard steel compositions, hardness numbers conversions. *Ryerson*

593. Steel Bars

12-page booklet on properties, advantages, applications of cold-worked, furnace-treated steel bars. *LaSalle*

594. Steel 52100

New stock list on 52100 tubing, bars, and ring forgings. *Peterson Steels*

595. Steel Melting

Bulletin II-C on high-frequency induction furnaces for steel and ferrous alloys. *Ajax Electrothermic*

596. Steel Treating

Bulletin on flame hardening, induction hardening, carbonitriding, nitriding, liquid carburizing. *Chapmanizing Lakeside Steel Improvement*

597. Steel Tubing

48-page Handbook F-3 on fabricating and forging steel tubing. Bending, shaping, cutting and joining operations described. *Ohio Seamless Tube*

598. Steels

16-page booklet lists and describes major stainless, tool and electrical steels. *Allegheny Ludlum*

599. Straightening Machines

16-page bulletin on shape straighteners, stretcher levelers; how shape straightening works. *Medart*

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Catalog gives complete technical data on subzero metal treatment. *Cincinnati Sub-Zero Products*

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Literature on 3-min. determinator for use with combustion furnace. *Dieter*

602. Temperature Control

Bulletin 70 on temperature monitoring system. *Thermo Electric*

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Catalog of pyrometer supplies gives data on thermocouples, protection tubes, other accessories. *Arklay S. Richards*

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22-page Bulletin 46 on instrumentation, tools and accessories for mechanical testing machines. *Tinius Olsen*

609. Testing Machines

Bulletin on Brinell hardness, ductility, compression, tensile, universal, transverse, hydrostatic proving instruments. *Steel City Testing Machines*

610. Testing Machines

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Production of titanium and its powders, and special properties. *Metals Disintegrating*

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28-page guide to qualities and sizes available. *Uddeholm*

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Data sheets on high speed, hot work, air, oil and water hardening tool steel, alloy steels, machinery steels, stainless steels, welding rods. *Crucible Steel*

620. Tool Steel

60-page booklet on high-speed, hot work, cold work, shock resisting, carbon and low-alloy tool steels. *Jessop*

621. Tool Steel

48-page Catalog No. 6 on cold finished drill rod and other steels. *Pittsburgh Tool Steel Wire*

622. Tool Steel

36-page booklet on properties and applications of high speed steels, nonferrous cutting materials and carbides. *Allegheny Ludlum*

623. Tool Steel Selector

Selector is handy chart featuring general and heat treating data on nondeforming, water hardening, shock-resistant, hot work, high-speed tool and hollow die steels. *A. Milne & Co.*

624. Torsion Tester

Bulletin RT-10-54 on new 60,000 in.-lb. precision torsion tester. *Riehle*

625. Tubing

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Brochure on pressure containers and special shapes on the ends of steel tubing. *Marson Co.*

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Data on properties and uses of 95% tungsten alloy, balance nickel and copper. *Firth Sterling*

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Wall chart gives data for inert-gas arc-welding of aluminum, magnesium, stainless steel with pure and thoriated tungsten electrodes. *Sylvania*

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54-page manual on welding processes for stainless with recommendations and settings for arc, spot and pulsation welding. Soldering and brazing. *Republic Steel*

643. Welding Supplies

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320	346	372	398	424	450	476	502	528	554	580	606	632	
321	347	373	399	425	451	477	503	529	555	581	607	633	
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323	349	375	401	427	453	479	505	531	557	583	609	635	
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612. Thermocouples

Catalog 30H on thermocouples, quick-coupling connectors, panels, pyrometers and extension wires. *Thermo Electric*

613. Tin

20-page booklet describes mining of tin and its present use by American industry. *Malayan Tin Bureau*

614. Titanium and Zirconium

16-page bulletin, "The Hydromet Process", on titanium and zirconium metals and hydrides, and other metallurgical hydrides. *Metal Hydrides*

615. Titanium Powder

Production of titanium and its powders, and special properties. *Metals Disintegrating*

616. Titanium Tubing

Bulletin No. 42 on small tubing of titanium; processing, fabrication, characteristics. *Superior Tube*

617. Tool & Die Steels

28-page guide to qualities and sizes available. *Uddeholm*

618. Tool Dressing

Bulletin on package equipment for tool dressing—forging hammer and furnace, heat treat furnace, quench tank, tempering furnace, tool grinder. *Lobdell United*

619. Tool Steel

Data sheets on high speed, hot work, air, oil and water hardening tool steel, alloy steels, machinery steels, stainless steels, welding rods. *Crucible Steel*

620. Tool Steel

60-page booklet on high-speed, hot work, cold work, shock resisting, carbon and low-alloy tool steels. *Jessop*

621. Tool Steel

48-page Catalog No. 6 on cold finished drill rod and other steels. *Pittsburgh Tool Steel Wire*

622. Tool Steel

36-page booklet on properties and applications of high speed steels, nonferrous cutting materials and carbides. *Allegheny Ludlum*

623. Tool Steel Selector

Selector is handy chart featuring general and heat treating data on nondeforming, water hardening, shock-resistant, hot work, high-speed tool and hollow die steels. *A. Milne & Co.*

624. Torsion Tester

Bulletin RT-10-54 on new 60,000 in.-lb. precision torsion tester. *Riehle*

625. Tubing

52-page "Handbook of Seamless Steel Tubing". 26 pages of data. *Timken*

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Brochure on pressure containers and special shapes on the ends of steel tubing. *Marietta Co.*

627. Tungsten Alloy

Data on properties and uses of 95% tungsten alloy, balance nickel and copper. *Firth Sterling*

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Wall chart gives data for inert-gas arc-welding of aluminum, magnesium, stainless steel with pure and thoriated tungsten electrodes. *Sylvania*

629. Ultrasonic Cleaning

Folder on principles and methods of metal cleaning by application of ultrasonic energy. *Detrex*

630. Ultrasonic Testing

Bulletin No. 50-105 on application of ultrasonic testing to manufacture, maintenance and quality control. *Sperry Products*

631. Universal Machine

Bulletin 118 on machine for turning, grinding, milling, drilling and other operations. *Newage*

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Bulletin on principles, production steps, applications, equipment. *National Research*

633. Vacuum Furnaces

Bulletin on application of vacuum furnaces to the processing of metals. *Stokes*

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8-page bulletin on vacuum impregnation and agitation equipment. *J. P. Devine*

635. Vacuum Impregnating

20-page booklet explains vacuum impregnation, equipment used and its application. *Stokes*

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24-page Bulletin V51 on high-vacuum pumps and accessories. *Kinney Mfg.*

637. Vanadium in Steel

189-page book on properties of ferrous alloys containing vanadium and their applications. *Vanadium Corp.*

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12-page brochure on 25 steel, iron, aluminum and chemical products. Composition and applications. *Vanadium Corp.*

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12-page booklet gives properties, heat treatment, effect of tempering, hardness of chromium-vanadium tool steels. *Vanadium-Alloys Steel*

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12-page bulletin, ADC 717, on method of inert-gas-shielded metal-arc welding. Economics of process and equipment. *Air Reduction Sales*

641. Welding Copper

24-page booklet on oxyacetylene, carbon-arc and metal-arc welding techniques for copper and copper alloys. *Revere*

642. Welding Stainless

54-page manual on welding processes for stainless with recommendations and settings for arc, spot and pulsation welding. Soldering and brazing. *Republic Steel*

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METHODS OF MANUFACTURE

Electric Furnace

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PLATE STRIP SHEET

X X X
X X X

SPECIAL QUALITIES

Aircraft

Armor

Bearing

Drawing

Flange and Firebox

Metal Cutting Saw

Razor Blade

Other Special Qualities

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

TREATMENTS: INDIVIDUAL OR COMBINED

Quenched and Tempered

Annealed

Spheroidize Annealed

Normalized

Stress Relieved

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

CONDITIONS: INDIVIDUAL OR COMBINED

Hot Rolled

Straight Lengths

Coiled

Flattened or Leveled

Gas or Special Cutting

Pickled

Sand Blasted

Oiled

Formed, Machined or Other Special Conditions

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

SPECIFICATIONS—REQUIREMENTS: INDIVIDUAL OR COMBINED

Grain Size

Macro-Etch

Micro-Cleanliness

Restricted Chemical Analysis

Special Mechanical Tests

Impacts

Tensile Tests

Bend Tests

AISI-Govt.-ASTM-SAE

Special Specifications

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

X X X
X X X

alloy steel plate, sheet and strip!

Just specify
U·S·S CARILLOY steels

Glance down the accompanying list of qualities, treatments, conditions and specification requirements that can be furnished in U·S·S CARILLOY plate, sheet and strip. This is the widest selection of flat rolled Alloy Steel products you can secure from any one producer. Our unmatched mill flexibility and size range enable you to order anything from a razor blade strip to a plate for a battleship. This streamlines your purchasing, assures consistent quality and simplifies your manufacturing prob-

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Any time you have a metallurgical or fabricating problem, call in a United States Steel Service Metallurgist. He has an extensive knowledge of all types of Alloy Steels and can help cut costs by offering suggestions to assist your engineering and production people.

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with a custom-made

GOLDMAN AGITATOR

JUST as if they were caught in a cataract, liquids are tossed around violently in a Goldman Agitator. And the mixing is rapid and thorough.

The Goldman Agitator is entirely new in principle. Baffles, which position themselves automatically, abruptly halt the whirlpool motion of the liquid on the surface, "folding" the liquid back on itself and then directing it downward through the cylindrical extension. Here, the stirring paddles pick up the liquid and create the rotary flow necessary to return the liquid to the baffles.

This unconventional cataract motion of the Goldman Agitator mixes liquid both vertically and horizontally; cuts mixing time and production costs. For example, when washing light oil with sulfuric acid and caustic, the Goldman Agitator cuts mixing time to a fraction of the time required in conventional mixers.

Product quality can be improved by using a Goldman Agitator; liquids are mixed with a completeness that cannot be approached by conventional mixers. We invite your inquiry concerning any of your problems in nitration . . . gas absorption . . . saturation . . . evaporation . . . distillation . . . concentration . . . crystallizing . . . dissolving, etc.

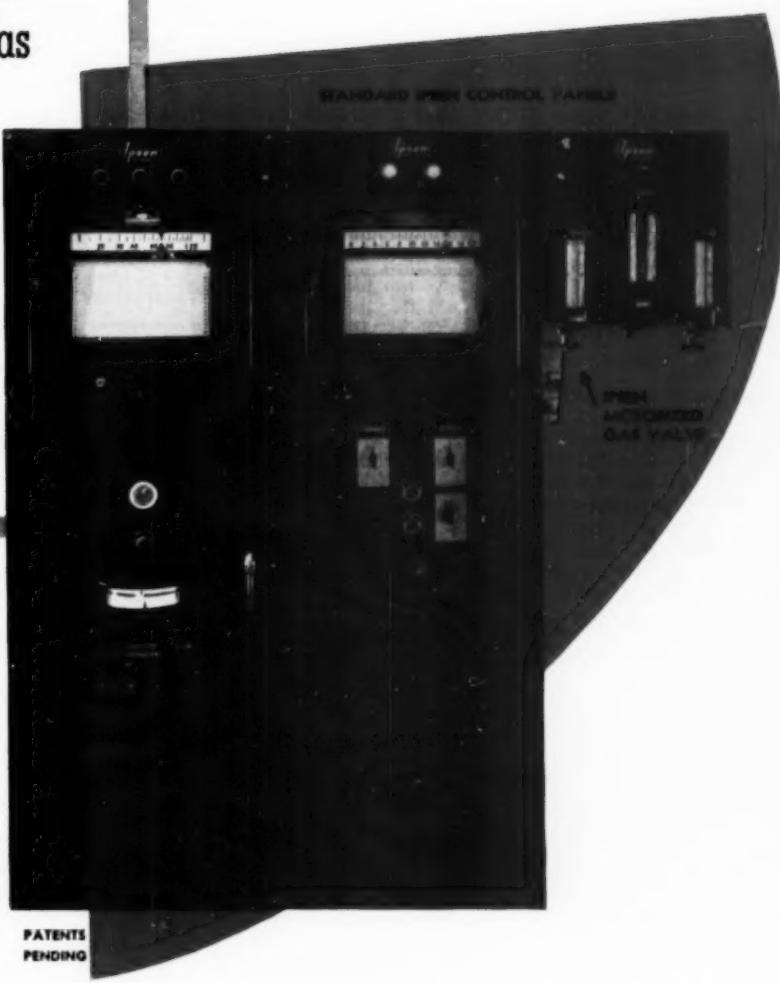
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**your tapped threads
will do things they
could never do before**

Heli-Coil* Screw Thread Inserts Are Your Answer To Almost Every Threaded Fastening Problem — Here's How They Enable You To Improve Product Design And Cut Costs —

Use Heli-Coil Inserts, and you get unparalleled strength in threaded assemblies.

Use Heli-Coil Inserts, and you can use fewer, smaller, shorter screws, bolts or studs, smaller bosses or flanges.

Use Heli-Coil Inserts, and you have permanent thread life — positive protection against stripping, vibration and wear.

Use Heli-Coil Inserts, and your threads are forever free from galling or seizure, unaffected by corrosion.

HERE ARE THE FACTS

What HELI-COIL Inserts ARE — Precision-formed coils of stainless steel or phosphor bronze wire having a diamond-shaped cross-section. They line the tapped hole and present a strong, accurate, standard internal thread to the screw or stud. *Heli-Coil* Inserts are made for Class 2, 3, 2B or 3B applications in National or Unified threads, for automotive and aviation spark plug threads, and for straight and taper pipe threads.

Where To USE THEM — Most importantly, wherever threaded fastenings are necessary in relatively soft materials — aluminum, magnesium, wood, plastics.

Whenever screws must frequently be removed or replaced.

Wherever there is any danger of thread failure due to stress, vibration, fatigue, corrosion or wear.

Wherever you want to increase strength of fastening without increasing weight or bulk.

HOW You Install Them — It's easy. Drill the hole. Tap it with a *Heli-Coil* tap. Then wind the insert into the hole with a hand or power inserting tool.

What HELI-COIL Inserts mean to the Design Engineer

You can use shorter, less bulky thread engagements, consequently lighter bosses and smaller flanges. You can eliminate costly solid bushings. No staking is required. You eliminate secondary machining operations. Often you can use cap screws in place of stud- or bolt-and-nut assemblies.

Inserts require much less space than other types of bushings. They are up to 75% lighter in weight than solid bushings. They assure added strength for any tapped thread, even in short thread engagements. You eliminate thread wear, minimize fatigue.

These proven, precision inserts offer you a world of possibilities for product improvement at low cost.

SALVAGE AND REPAIR

Threads improperly tapped on production lines can be repaired quickly and inexpensively simply by re-drilling, tapping and winding in *Heli-Coil* Inserts providing a better-than-original thread of original thread size. Thus, for a few cents, costly material is salvaged without interruption to production; no need for over-size studs or cap screws. Threads stripped or worn in the field can be repaired quickly and easily the same way.

EXAMPLES OF SUCCESSFUL PRODUCT IMPROVEMENT WITH HELI-COIL INSERTS



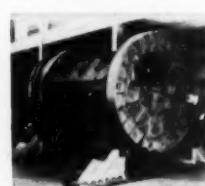
INGERSOLL-RAND:

Improved its Impactool with *Heli-Coil* Inserts in the aluminum housing which is subject to severe vibration. In addition, the housing was lightened, seizing and galling were eliminated.



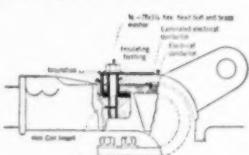
AIR REDUCTION CO.:

Improved an arc welder design with *Heli-Coil* Inserts, using them to protect tapped threads in plastic and also to lock a bushing in place.



AJAX ENGINEERING CO.:

Overcame thread corrosion due to heat and magnetic influences in induction furnaces by using *Heli-Coil* Inserts.



PROGRESSIVE WELDER SALES CO.:

Reduced the weight of a product 66% by using *Heli-Coil* Inserts in a special metal alloy.

3 Ways to get started with... HELI-COIL INSERTS

1. Ask your *Heli-Coil* Engineering Representative to discuss the use of *Heli-Coil* Inserts to improve product design. There's no obligation.
2. Send for your free copy of *Heli-Coil* Catalog. Contains design data, specifications, facts on *Heli-Coil* Inserts, Taps, Inserting Tools and gages, sizes and classes of fit.
3. Get on the list for "Heli-Coil" — a periodical review of case histories — shows and tells you who uses *Heli-Coil* Inserts — and why.



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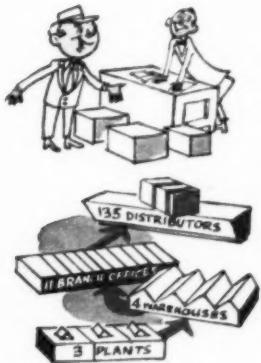
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money makes *tooling* the key to profit!

Only Firth Sterling can serve you so completely in solving the tooling problems that enable you to make production profits . . . for these six convincing reasons:



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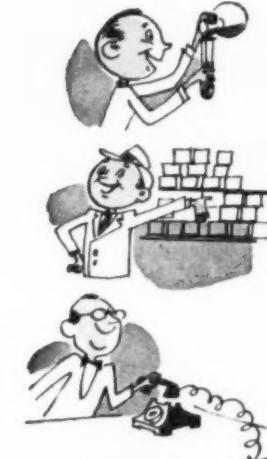
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ONE SOURCE MAKES SENSE Yes, only Firth Sterling can so adequately provide one-stop, one-source-of-supply tooling service with its assurance of unbiased recommendations, simplified lower-cost ordering . . . resulting in better, faster, cheaper production. It makes sense, doesn't it? Ask Firth Sterling to analyze your tooling problems . . . to produce *more for less*.



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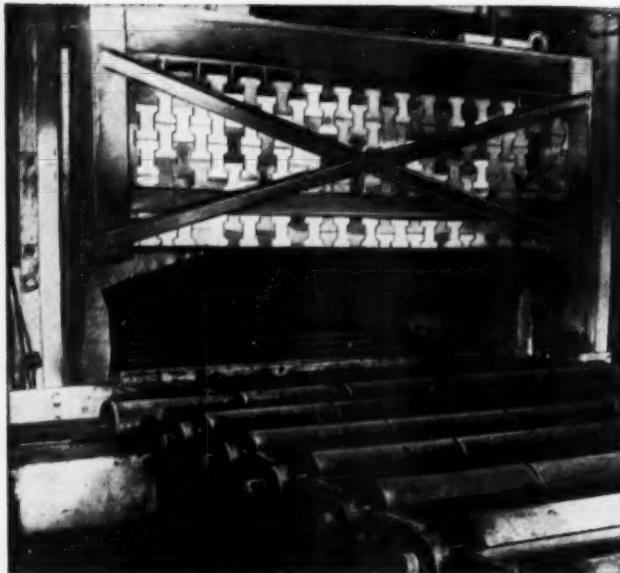
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Zirconium

Zirconium

Lower Maintenance Costs with HAYNES Alloys

Trade-Mark



3800 Hours at 2150 deg. F.—HASTELLOY Alloy X rollers have been conveying metal sheet through this annealing furnace for 3800 hours. The rollers are subjected to thermal and mechanical shock, 2150 deg. F. temperatures, and exposed to an oxidizing and corrosive atmosphere. They are still in good condition.

HAYNES Alloys operate efficiently where ordinary metals quickly wear away, corrode, or disintegrate under high-temperatures. They can help you keep production moving and cut maintenance costs.

HAYNES Hard-Facing Alloys protect hot shear blades, dies, draw rings, punches, shafts, and other steel mill equipment from the effects of abrasion, heat, and impact.

HASTELLOY Alloys have high strength and remarkable resistance to severe corrosives and thermal shock. Use them to increase the service life of your pickling equipment.

HAYNES High-Temperature Alloys are strong at temperatures up to 1800 deg. F., have high stress to rupture properties, excellent resistance to oxidation, and low creep rate. They give outstanding service in heat-treating furnaces.

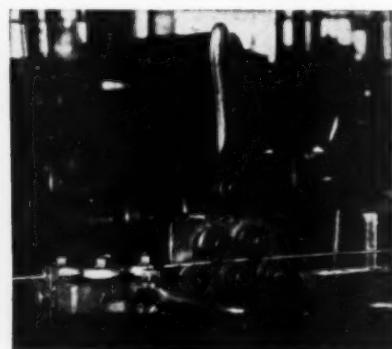
For full information on forms, prices, and properties, contact the sales office nearest you.



Guide 200 Tons of Steel—Entry guides hard-faced with HAYNES STELLITE Alloy No. 6 have lasted 4 to 5 times longer than unprotected ones in guiding hot bars. The guides are exposed to abrasion and heat.



16 to 1 Life in Hot H₂SO₄—HASTELLOY Alloy paddles show no loss in cross-section after carrying tubing in and out of a pickling tank for 4 years. Other materials had to be replaced after only 3 months' service.



10 Years Service—Wire-straightening rolls cast from HAYNES STELLITE Alloy are still in good shape after 10 years' service. Steel rolls, previously used on this job, wore out every three or four months.

HAYNES
TRADE-MARK
alloys

"Haynes," "Haynes Stellite," and "Hastelloy" are trade-marks of Union Carbide and Carbon Corporation.

Haynes Stellite Company
A Division of
Union Carbide and Carbon Corporation

UCC

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... a New HARDENABLE SILVER ALLOY

IMPORTANT PROPERTIES OF SILVER-MAG-NICKEL

- ✓ Oxidation Hardenable
- ✓ High Electrical Conductivity — 70%
- ✓ High Thermal Conductivity
- ✓ Hardnesses to 70 — Rockwell 30 T
- ✓ Tensile Strengths to 70,000 psi
- ✓ Corrosion Resistance Like Fine Silver
- ✓ Hardness Unaffected by Silver Brazing

SILVER-MAG-NICKEL is its name. As you receive it, it is soft and ductile, like fine silver. Fabricate your most intricate parts, then oxidation harden them and this new alloy will hold its temper permanently. This hardness is not disturbed even when subsequent elevated temperatures are encountered.

SILVER-MAG-NICKEL has excellent thermal and electrical conductivity. Its corrosion resistance is equal to that of fine silver. It is available in wire and strip in thicknesses down to .002".

Have you an application where SILVER-MAG-NICKEL can be used to advantage? See the list of properties to the left. Write giving full details of your potential application. Our engineers will be glad to discuss these properties with you.



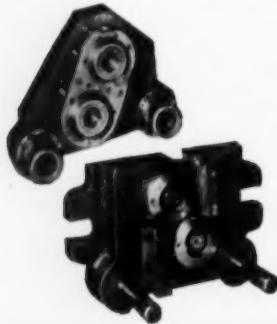
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For Every Tool and Die Job There's a BETHLEHEM TOOL STEEL

Some Bethlehem Tool Steels are general-purpose grades; others have properties that fit them for severe or unusual operating conditions. Whatever your tool and die jobs, there's a Bethlehem Tool Steel that will give you top performance at least cost. We make a complete line:



Made from our BTR oil-hardening tool steel, this die blanked and formed nearly 8 million bottle caps from tin plate before redressing was needed. One of our most popular general-purpose grades, BTR has good wear-resistance and shock-resistance.

ALLOY STEELS

All AISI and Special Analyses

Bethlehem can supply whatever you require in the way of alloy steels. We make the full range of AISI and special analyses, open-hearth and electric-furnace, hot-rolled and cold-finished.

In addition, we are always ready to supply helpful information to alloy-steel users. If you have a problem related to the selection or processing of alloy steels a Bethlehem engineer will gladly talk it over with you.

MAYARI R

Makes it Lighter, Stronger, Longer Lasting

Every day new uses are found for Mayari R, Bethlehem's low-alloy, high-strength steel. It has almost twice the yield point of structural-grade carbon steel, and from five to six times the resistance to atmospheric-corrosion. It forms and welds readily, and comes in sheets, plates, structurals, cold-formed shapes and bars.

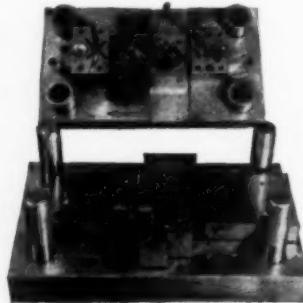
A WELDMENT MAY BE THE ANSWER

Bethlehem Weldments eliminate excess weight without sacrifice of rigidity, and serve either as simple parts or as units of intricate assemblies. They can be used either alone or in combination with forgings, castings, or structural shapes. They offer wide freedom of design, as the steel can be bent, pressed or shaped prior to welding without harm to its physical structure.

BETHLEHEM STEEL

Carbon and Carbon-Vanadium, Oil- and Air-Hardening, Shock-Resisting, Hot-Work, High Speed and Special-Purpose. And when you have a problem in the selection or treatment of tool steel, the experience of our technical staff is yours to call on.

This progressive die pierces, blanks and forms parts from stainless-steel strip. The long-wearing punches are made from Lehigh H, our popular high-carbon, high-chromium steel. All other parts are made of A-H5, Bethlehem's 5 pct chromium air-hardening grade.



COLD-FORMED SHAPES

Solve Many a Production Problem

Bethlehem Cold-Formed Shapes are regular or irregular shapes, formed cold from steel sheets, strip or plates. They have relatively smooth surface finish, practically free of scale and rust. They have a good strength-weight ratio, and are easy to weld and assemble.

CIRCULAR BLANKS

Made by Forging-Rolling Process

The process by which these blanks are made, combining forging and rolling with the benefits of both, imparts a tough structure and homogeneity, with superior strength, often making possible thinner sections and a saving in weight. Use them for gears, crane wheels, sheave wheels, flywheels, brake drums, rotors, tire molds and similar uses.

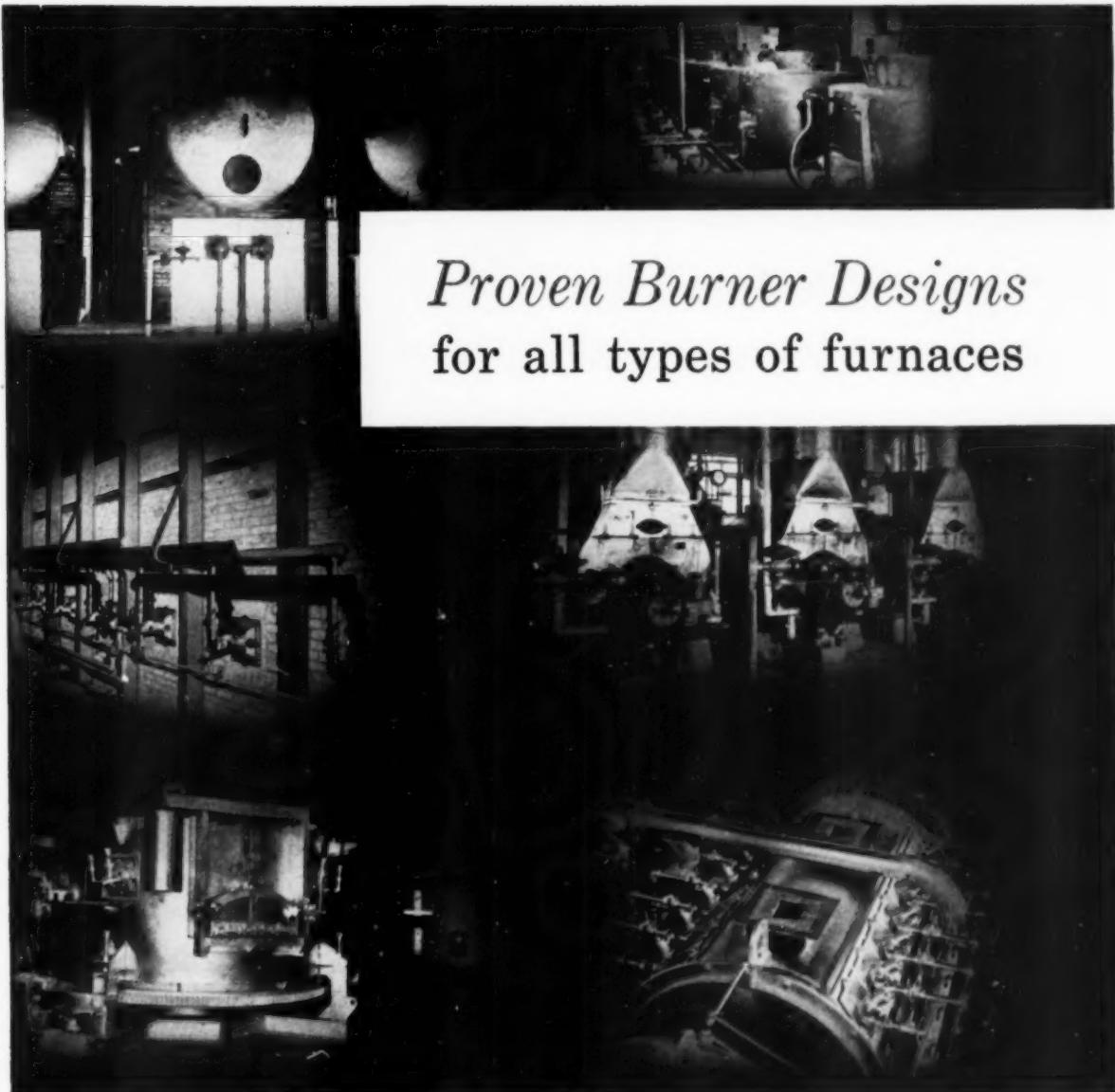
FORGINGS IN A WIDE RANGE

The Bethlehem forge shops turn out forgings ranging from among the smallest made to heavyweights of 100 tons or more. We make press forgings, hammer forgings, and closed-die forgings—all with the same exacting care. Carbon or alloy grades. Shipped either as-forged, or rough- or finish-machined.

BETHLEHEM STEEL COMPANY, BETHLEHEM, PA.

On the Pacific Coast Bethlehem products are sold by Bethlehem Pacific Coast Steel Corporation
Export Distributor: Bethlehem Steel Export Corporation





Proven Burner Designs for all types of furnaces

Whether your process calls for boilers or kilns, ovens or furnaces, NORTH AMERICAN has the right burners and the right combustion accessories for you.

Ceramic kilns, crucible furnaces, forge furnaces, frit furnaces, galvanizing kettles, glass lehrs, glass

tanks, heat treat furnaces, ovens and reverberatory furnaces, in all sizes and temperature ranges—are within NORTH AMERICAN's scope. Whether your needs are large or small, you can depend upon the skill and integrity of NORTH AMERICAN combustion engineers.



The

NORTH AMERICAN

Manufacturing Company

4455 East 71st St. • Cleveland 5, Ohio

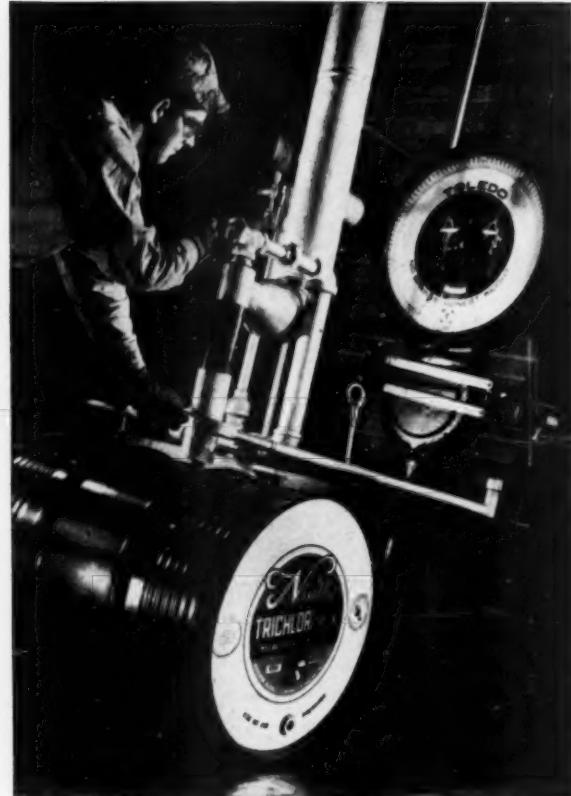
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with

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MINIMUM VAPOR LOSS
MAXIMUM SAFETY...

Nialk
TRICHLORethylene

Nialk TRICHLORethylene is the ideal solvent for removing from metal parts—quickly, safely and economically—waxes, oils, greases, gums, tars, metal chips and other foreign matter. It leaves parts clean, warm and dry, ready for immediate assembly, inspection or surface treatment.



Here are a few of the reasons why...

Its low boiling range (86.6°—87.8°C, based on standard ASTM tests) permits vaporization at low steam pressure. (Incidentally, the narrowness of this boiling range reflects Nialk TRICHLORethylene's high purity.)

Its low specific heat (less than $\frac{1}{4}$ that of water) means less power consumption.

Its low viscosity (0.58 centipoises at 20°C) and **low surface tension** (about 29 dynes per cm at 30°C) give rapid wetting of surfaces, plus thorough diffusion into pores and relatively inaccessible openings.

Its high vapor density (4.5 times that of air) assures

proper vapor level at all times, thus cutting vapor loss.

It has **no flash point** and **no fire point**, is classed as nonflammable at room temperature and only moderately flammable at higher temperatures. (Underwriters' Laboratories rating 3.)

Finally, it is **stable** and **completely re-usable** after distillation, and—whether you need a drum or a carload—you pay **no extra premium** for Nialk TRICHLORethylene's top quality. We will be happy to send you further information on Nialk TRICHLORethylene in terms of your own particular application.

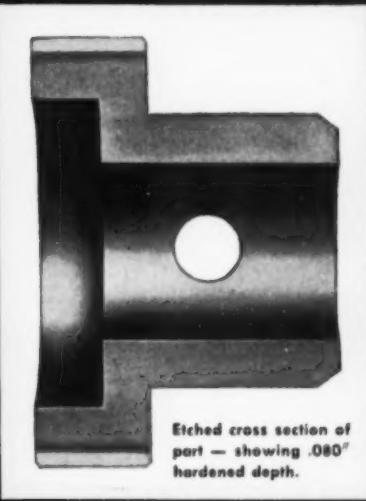
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NIALK Caustic Soda • NIALK TRICHLORethylene • NIAGATHAL® (Tetrachloro Phthalic Anhydride)

COSTS CUT

94%



Etched cross section of part — showing .080" hardened depth.

with TOCCO* Induction Heating

A cost reduction of 94% resulted when heat-treatment of this Corn Harvester part was changed from carburizing to TOCCO-hardening. Look at the unit cost breakdown:

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	CARBURIZING	TOCCO-Hardening
Degrease	\$0.0020	eliminated
Carburize	0.0200	eliminated
1st quench	0.0150	TOCCO, heat and quench \$0.0060
2nd quench	0.0150	eliminated
Draw	0.0050	eliminated (self-draw)
Shotblast	0.0035	eliminated
Internal Grind	0.0243	eliminated
External Grind	0.0166	eliminated
	<hr/> \$0.1014	<hr/> \$0.0060

"—Savings of 9½ cents per piece—
\$4770.00 on each 50,000 piece batch,
plus an hourly production increase
from 120 to 300 pieces per hour,
plus improved quality of the product
by virtue of the deeper case and
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For best results process your X-ray film in AnSCO X-ray Chemicals.



ANSCO LIQUADOL DEVELOPER is designed especially to render optimum density and contrast. Prepared in concentrated liquid form, Liquadol is ready for use when diluted with water. This simple operation gives you a fast-working developer with several times the capacity of powdered formulas.



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NEW! ANSCO POWDERED X-RAY FIXER! High capacity. Easy to mix. Free flowing. Less tendency to stain. Available now, in packages to make five gallons of working solution.

Ask your ANSCO representative for a demonstration—at YOUR convenience.

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1. Faster

This excellent X-ray film for industrial use permits shorter exposures, with or without lead screens.

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The higher contrast and finer grain of Superay "A" reveal the smallest defects, which means easier-reading radiographs.

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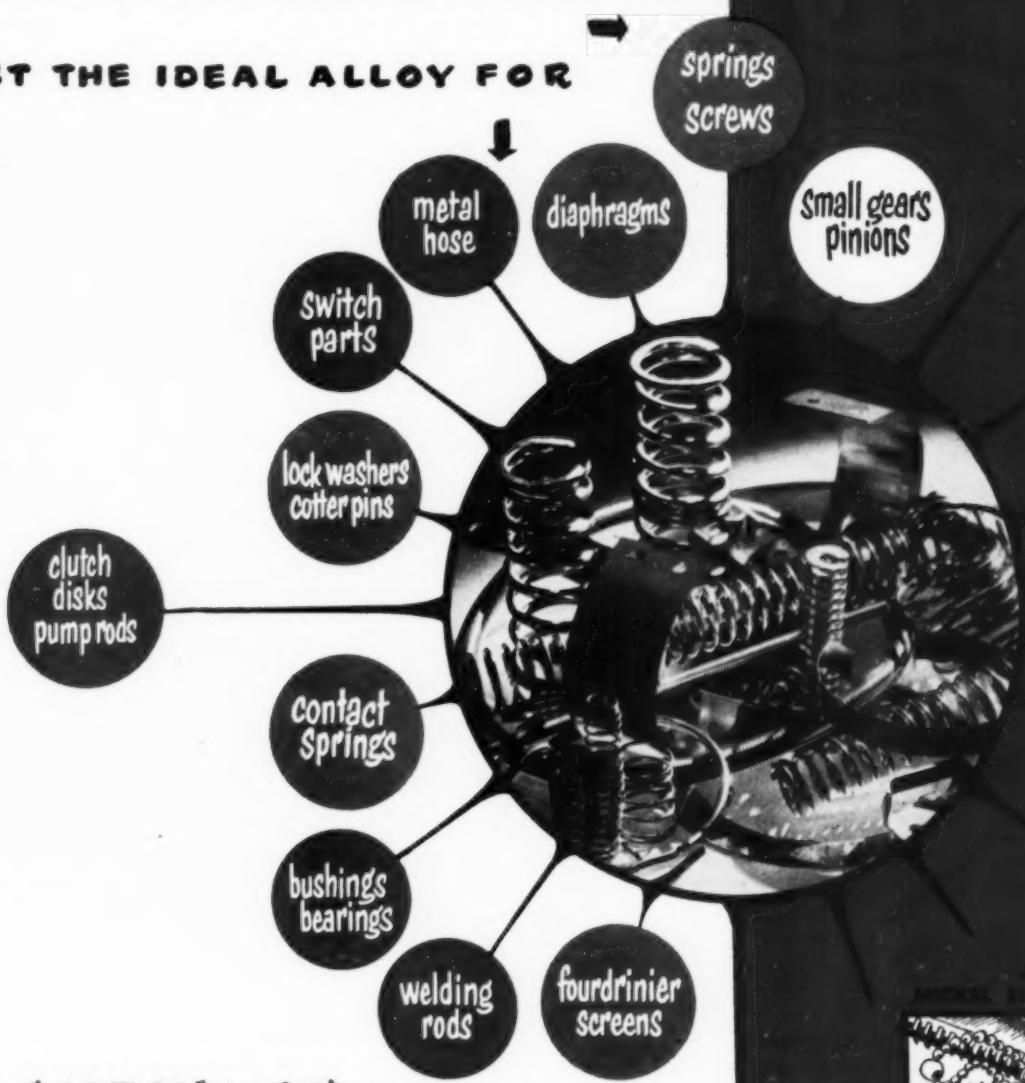
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Technical data are yours for the asking. Glad to furnish samples for tests, and our engineering department is ready to discuss your problem without obligation.

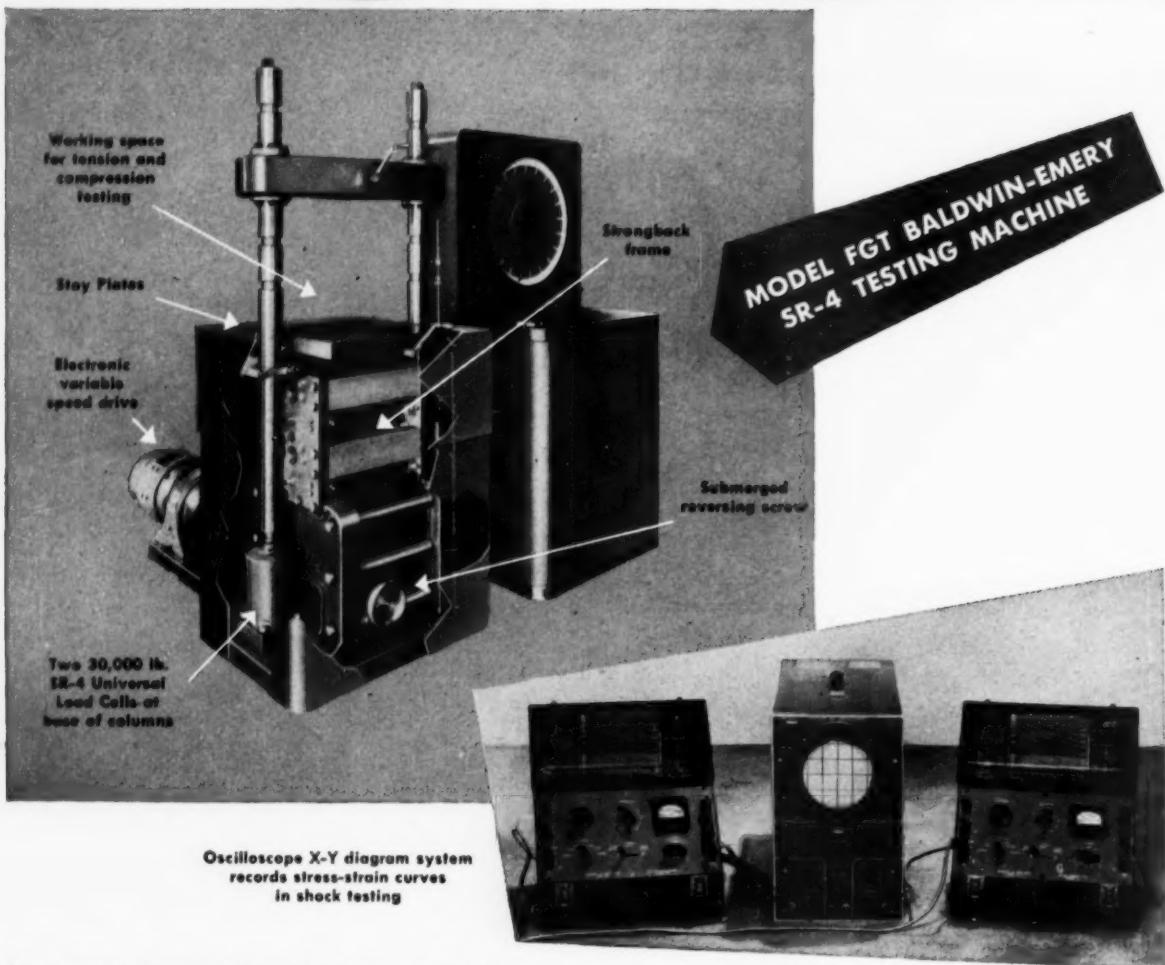
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ALLOYS
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NOW! A Machine Fast Enough for SHOCK Tests on Structures



The extraordinary high speed of response of this revolutionary new Baldwin-Emery universal testing machine, paired with an oscilloscopic X-Y diagram, enables it to measure and record shock tests on complete structures. Its SR-4 load cells and SR-4 type extensometer make it capable of responding to the rates required by shock conditions.

The load cells and extensometer feed signals to the oscilloscope through pre-amplifier circuits. An instantaneous stress-strain curve and its two axes then appear on the oscilloscope screen. It is possible to

have this screen photographed continually to record changes in the shape of the stress-strain curve as the structure itself changes.

Its unique aptness for such shock tests is one of the reasons why the FGT SR-4 Testing Machine is being recognized as *the greatest advance in materials testing equipment in twenty years*.

Full details on this latest contribution of Testing Headquarters are in Bulletin 4202. For your copy, write to Dept. 2224, Baldwin-Lima-Hamilton Corporation, Philadelphia 42, Pa.



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**...For ALL
Commercial
Metals Usually
Joined By
Soldering**

Already proved in actual use in virtually every type of practical application, this is the *ONLY* flux made for the permanent joining of every aluminum alloy regardless of soldering method —dip, torch, iron or furnace. No corrosive residue remains in most cases, and soldered parts can be used immediately after the soldering operation.

Unsurpassed for joining aluminum, Aluma-Flux* is equally efficient for soldering stainless steel, nickel, brass, copper, resistance wire, bare and galvanized steel, cast iron, and other ferrous alloys. It may be used for the fast and easy joining of unlike metals such as brass and aluminum.

Nothing else can match it!

Even when exposed to salt spray, high humidity, alkaline water and other normal corrosion-inducing conditions, aluminum joints made with Aluma-Flux produce little or no corrosive action.

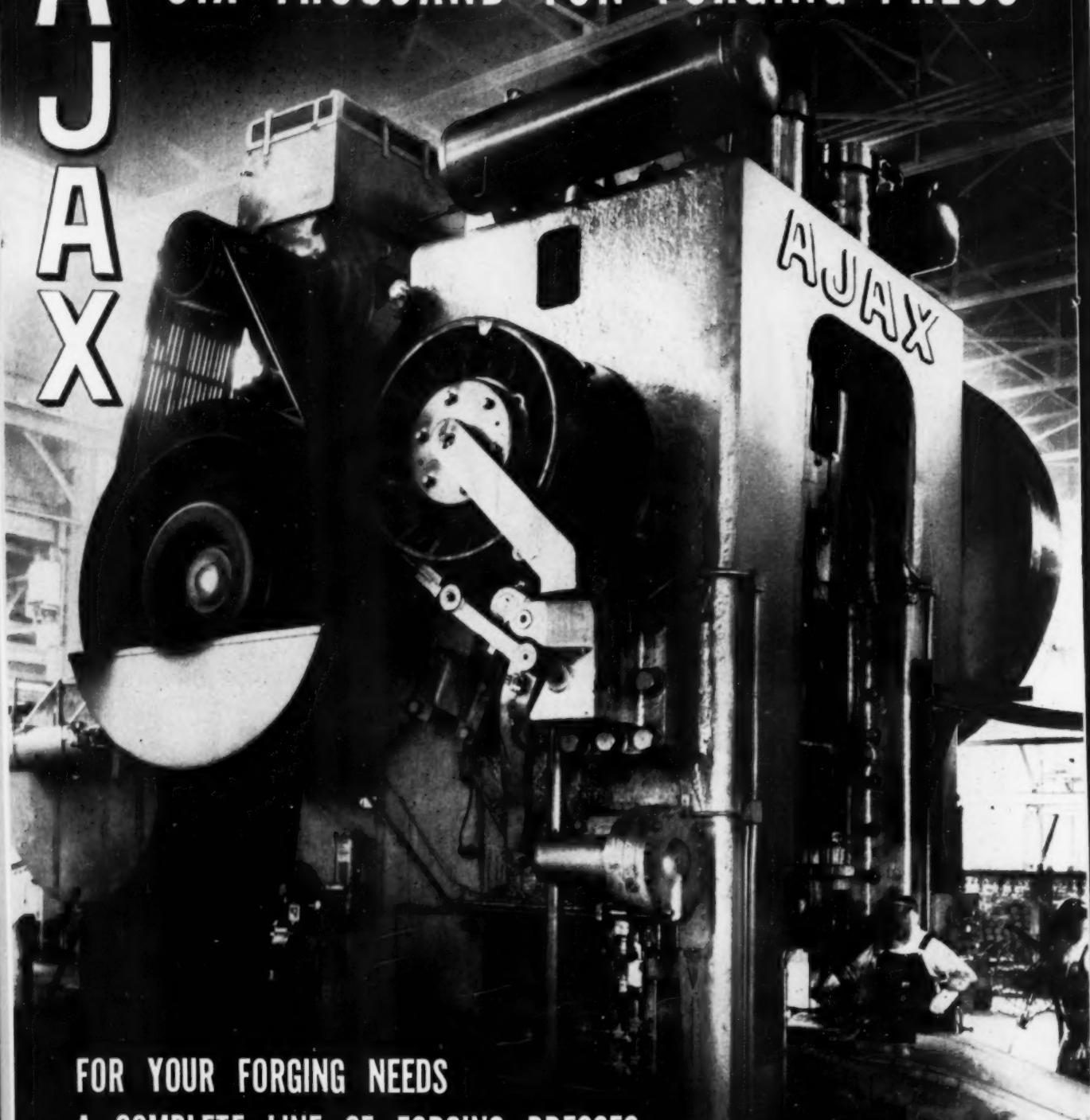
Practically any type of solder can be used. And because Aluma-Flux is non-hygroscopic—won't absorb water—it can be stored indefinitely without change of weight or fluxing efficiency.

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Aluma-Flux Is Ready For Immediate Shipment In Convenient Containers

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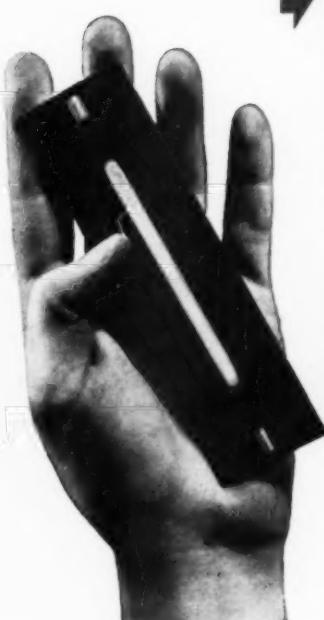


Let GLOBAR ENGINEERING help you solve it...to *your* satisfaction

GLOBAR® Silicon Carbide Heating Elements by CARBORUNDUM, operating in modern electric furnaces, have aided in solving industrial heating problems for over 30 years. Our engineers work closely with you, and with the furnace manufacturer of your choice, to determine the best solution. What do you require? More production...faster processing...higher temperatures...more

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GLOBAR® Heating Elements
by **CARBORUNDUM**
REGISTERED TRADE MARK



IT TAKES MORE THAN THESE



...to build a bridge

IT TAKES MORE THAN THESE



...to heat treat metals

BOTH MUST HAVE THE VITAL INGREDIENTS — SKILL AND EXPERIENCE

It is a sad fact that many skilled production men and managers have been, in recent years, badly misled into believing that given a furnace — a quench tank — a salt bath, and a corner of floor space — they can promptly and easily fulfill their heat treating requirements. Aggressive and misleading selling by some furnace and equipment manufacturers (fortunately only a small minority) has encouraged this misconception that equipment and materials alone are the essential factors in heat treating operations.

The cold fact is, that without the proper combination of human operational skill and technical knowledge developed over years of practical experience, even the best, most mechanical, most modern heat treating equipment becomes a potent menace to your product and your profit margin.

Careful evaluation of all the factors involved in any heat treating operation — large or small — always reveals that TECHNICAL SKILL BORN OF EXPERIENCE tops the list.

Make it head your list when you are analyzing the pros and cons of the question "Shall we do our own heat treating?" Write for a useful folder — "Facts and Figures on Heat Treating Costs".

THERE'S A HEAT TREATING SPECIALIST NEAR YOUR PLANT

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Anderson Steel Treating Co.
Detroit, Michigan
Benedict-Miller, Inc.
Lyndhurst, New Jersey
Commercial Metal Treating, Inc.
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Commercial Steel Treating Corp.
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Cook Heat Treating Co. of Texas
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Greenman Steel Treating Company
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Stanley P. Rockwell Company
Hartford 5, Connecticut
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"Tailored by Dempsey"



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Springfield 1, Mass.

LIST NO. 79 ON INFO-COUPON PAGE 64

FOR ALL YOUR
BASKET and FIXTURE
NEEDS . . .

WIRETEX can meet all your plating and heat treating basket and fixture requirements, whether your need is for a small or large unit; standard or custom built; to resist acid, heat, abrasion or exposure; in every weave, metal and alloy.

May we study your requirements and submit our recommendations? New catalog available.

Wiretex mfg. co.

5 Mason St., Bridgeport 5, Conn.

LIST NO. 114 ON INFO-COUPON PAGE 64

"Carburizing Costs
MUST COME DOWN!"

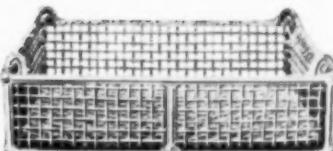


START SAVING TODAY by using Park Non-Burning Carburizers and cut your consumption of compound up to 50%. Low shrinkage losses with additions as low as 1 to 16. Write for bulletin.

PARK CHEMICAL COMPANY
8074 Military, Detroit 4, Michigan

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Call Wiretex



SERVING INDUSTRY WITH:

* Baskets * Retorts * Muffles
* Grids * Screens * Racks
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HEAT TREATING
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LIST NO. 19 ON INFO-COUPON PAGE 64

Upton

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the most advanced
Salt Bath Furnaces
FOR

BATCH
TYPE
WORK

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O
ALUMINUM
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UPTON ELECTRIC FURNACE CO.
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Phone: Diamond 1-2520

LIST NO. 20 ON INFO-COUPON PAGE 64

Instruments and Controllers for heat treating furnaces



A complete summary of Hays products applicable to processes such as annealing, brazing and calorizing. Scope includes various methods of firing (under-fired, over-fired, side-fired), fuel burned (gas, coal, oil), and type of furnace (continuous, rotary hearth, slab heating, etc.).

Hays complete line of draft gages, flow gages and meters (for high and low pressure gases and liquids), portable gas analyzers and automatic CO₂ recorders are covered.

Write for bulletin 51-750-51

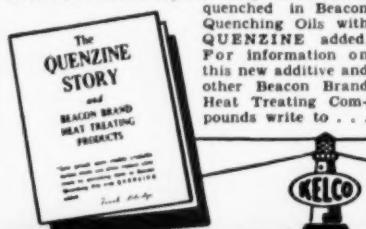
THE HAYS CORPORATION
McNamee City 24, Indiana

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FREE

the QUENZINE STORY

Low priced, more readily available carbon steels can often replace alloy steels when quenched in Beacon Quenching Oils with QUENZINE added. For information on this new additive and other Beacon Brand Heat Treating Compounds write to . . .



ALDRIDGE
INDUSTRIAL OILS, Inc.

3401 W. 140th St., Cleveland 11, Ohio

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HEAT TREATING!

- ★ Carburizing Salts
- ★ Neutral Salts
- ★ Tempering Salts

Faster more fluid baths!
Free washing!

Send for FREE Literature TODAY!

Swift
INDUSTRIAL CANTON CONNECTICUT

LIST NO. 92 ON INFO-COUPON PAGE 64

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Name it...
WE'LL
Supply it!

We make containers and fixtures of all types—
for handling parts in heat treating, quenching,
pickling, washing and anodizing operations.

If what you need isn't shown in our catalog,
we'll design and build it for you.

REPRESENTATIVES IN PRINCIPAL CITIES

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RETORTS

LIST NO. 12 ON INFO-COUPON PAGE 64

INDUSTRIAL FUEL BURNING EQUIPMENT

Designed FOR YOUR SPECIFIC REQUIREMENTS

- Motor-Mix Burners
- Model DA Mixers
- Western Safety Valves
- Injector-Mix Burners
- Flame Retention Nozzles
- Accessories
- Inspirator-Mix Burners
- Blowers
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- Custom Built Equipment

Free descriptive literature on request

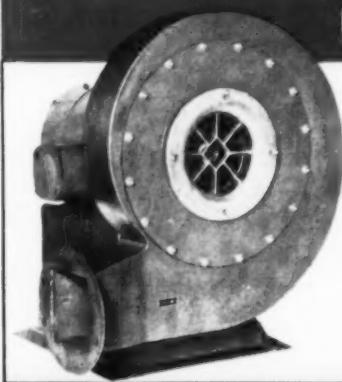


WESTERN PRODUCTS, Inc.

General Office 549 W. Washington Blvd.
New Castle, Ind. Chicago 6, Ill.

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Combustion Air Blowers



Single Stage
8 oz. to 20 oz. Pressures

- Designed to meet your capacity and pressure requirements.
- Maximum Efficiency—power consumption is proportional to air volume delivery
- Constant Pressures assured through properly designed case, air inlet and impeller

Write for Bulletin 100-53

Manufactured by

WESTERN PRODUCTS, INC.
NEW CASTLE, IND.

LIST NO. 115 ON INFO-COUPON PAGE 64

Expand Your Plant Potential

WITH *Cooley*

ELECTRIC HEAT TREATING FURNACES

fast... inexpensive way to expand your plant facilities. Choose from 27 Models.

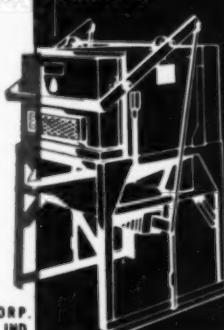
- For Instance:
1. You save time and money by keeping heat treat jobs for small parts in plant.
 2. It's easy to establish a new department at small cost in proportion to benefits which result.
 3. Cooley heat treat furnaces pay for themselves through savings in time and subcontracting costs.
 4. Heat treat operations are easily performed with Cooley designed furnaces.

Write now for Catalog giving complete details.

Cooley

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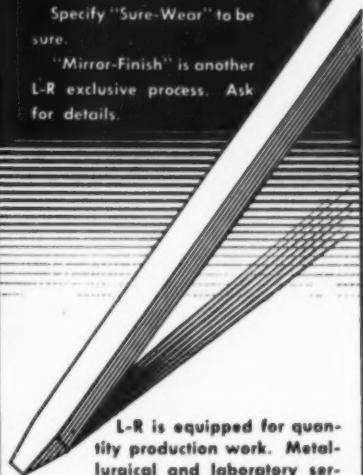
New!
Sure-Wear
Heat Treating

"Sure-Wear"—to ensure longer life in all types of high speed cutting tools!

L-R Heat Treating Co. research has developed a new process for heat treating of all types of high speed cutting tools to ensure longer tool life than ever before.

Specify "Sure-Wear" to be sure.

"Mirror-Finish" is another L-R exclusive process. Ask for details.



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Tool and Die Hardening . . .
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THE STORY OF MALCOMIZING

(See surface hardening stainless steel)



what it is . . . what it does . . . how it works
... how you can use it.

Write today for your copy of this 24-page booklet. Specific subjects discussed include . . . protecting the steel . . . selective Malcomizing . . . case depth . . . wear resistance . . . corrosion resistance . . . penetration of Malcomized steel.

A special "time history" section shows how nationally known manufacturers are specifying Malcomizing for the surface hardening of stainless steel.

Lindberg Steel Treating Co., covering Industrial America from coast to coast, with plants in Rochester, Chicago, St. Louis and Los Angeles, is now licensed to Malcomize for its customers. For particulars call your nearest Lindberg plant.

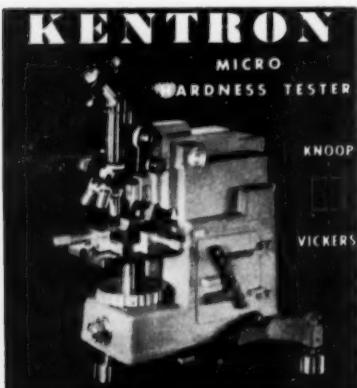
LINDBERG STEEL TREATING COMPANY

Chicago 7, Illinois, 222 N. LaSalle, Phone McGraw 6-3366; St. Louis 18, Missouri, 600 E. Taylor, Phone Franklin 6-2200; Los Angeles 23,

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Applies 1 to 10,000 gram loads
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The Torsion Balance Company
CLIFTON NEW JERSEY

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Spotlighting DETROIT'S BETTER HEAT TREATER



OFFERING FACILITIES FOR:

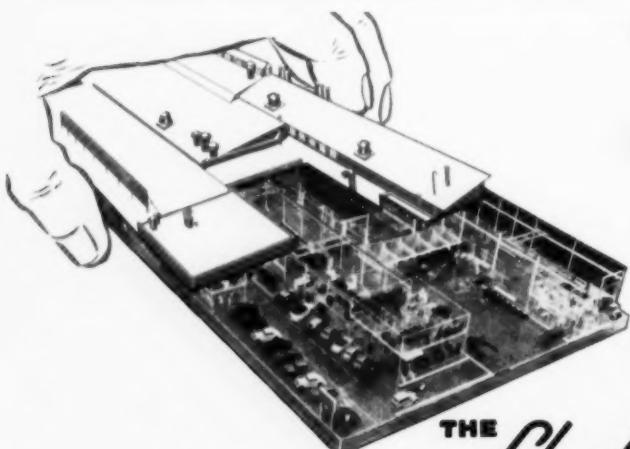
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- ALL TYPES OF HEAT TREATING CAN
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Your most comprehensive, complete
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Electronic Induction Hardening, Carbonitriding, Flame Hardening, Heat Treating, Bar Stock Treating and Straightening (mill lengths and sizes), Annealing, Stress Relieving, Normalizing, Pack, Gas or Liquid Carburizing, Nitriding, Speed Nitriding, Aerocasing, Chapmanizing, Cyaniding, Sand Blasting, Laboratory Physical Testing.

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SHEET METAL TESTER
 For Erichsen Test

Determines workability of ferrous, non-ferrous and fine metal sheets and strips to point of fracture. Reading—accurate to 0.0004" . . .



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If you want to perform Tensile or Brinell testing operations quickly and simply—contact

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ALL TYPES OF
 LABORATORY
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BY

Boder

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**Inspection
 Demagnetizing
 or Sorting
 PROBLEMS?
 SOLVED with**

**MAGNETIC ANALYSIS
 MULTI-METHOD EQUIPMENT**

Electronic Equipment for non-destructive production inspection of steel bars, wire rod, and tubing for mechanical faults, variations in composition and physical properties. Average inspection speed 120 ft. per minute.

Over 50 steel mills and fabricators are now using this equipment.

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Electrical Equipment for rapid and efficient demagnetizing of steel bars and tubing. When used with Magnetic Analysis Multi-Method Equipment, inspection and demagnetizing can be done in a single operation.

**MAGNETIC ANALYSIS
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Electronic Instruments for production sorting both ferrous and non-ferrous materials and parts for variation in composition, structure and thickness of sheet and plating.

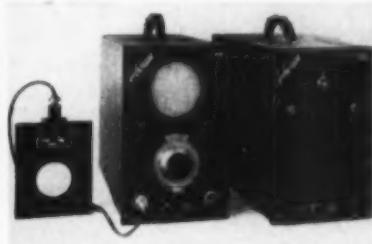
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 MAGNETISM DETECTORS**

Inexpensive pocket meters for indicating residual magnetism in ferrous materials and parts.

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It's Dice For The Best . . .
 in Metal Test Instruments



The CYCLOGRAPH (Model C)
 . . . for unscrambling metal mixups

This instrument permits truly high speed, non-destructive sorting of raw, semi-finished or finished parts by their metallurgical characteristics. With the new Automatic Sorter Unit speeds up to 300 pieces per minute are possible with the use of suitable feeding equipment. Used by leading industrial firms everywhere.

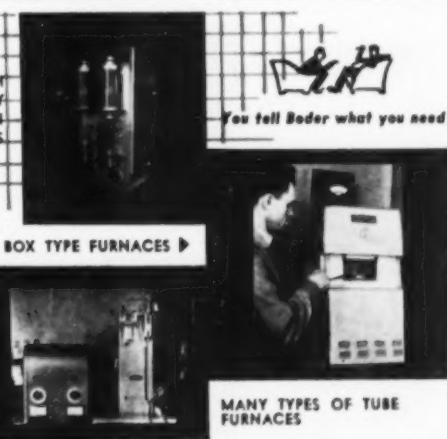
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"Non-destructive Testing and Measuring Instruments"

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 Automatic Type
 Tube Types—2000-5000° F.
 Box Types—3000-5000° F.
 Heat Treating
 Salt Bath Tempering
 Melting by Carbon Arc
 Metallurgical Experiments
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HIGH
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for rapid, accurate, non-destructive
THICKNESS MEASUREMENTS from oneside
and accelerated METAL CLEANING

VIDIGAGE Automatic Thickness Tester

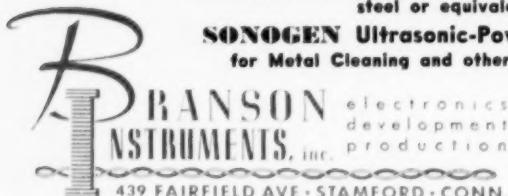
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SONOGEN Ultrasonic-Power Generator

for Metal Cleaning and other Industrial uses.



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Make expensive time-consuming operations like filing, grinding, polishing, blasting, buffing a thing of the past with New Amazing SUPERSHEEN SPEED FINISHING.

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cadmium and zinc

PROMAT C-42

permits zinc plating
twice as fast

PROSALT

improves, enriches
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ZINC BRIGHTENERS B-4 . . . B-4M

for brilliance, depth
and ECONOMY

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INDUSTRIAL ELECTROPLATED GOLD now answers production needs in many fields, aside from obvious applications in instrument-making and electronics. Unusual properties of electroplated gold — physical, thermal, chemical, electrical, optical and corrosion resistant as well as decorative — enable it to solve an amazing range of hitherto insoluble problems. Names of major industrialists taking advantage of new developments in gold electroplating are available from Technic, Inc. — originator of methods of electroplating gold with scientific accuracy. While this company does not process or finish metals, it does equip its patrons to perform these operations efficiently and economically — achieving unprecedented accuracy in control of quality, evenness, thickness, color, and hardness of gold deposits. Manufacturers who have not yet explored the high production values of electroplated gold are invited to send specific problems to find out exactly what benefits they can expect. Also available: "Electroplated Gold" data sheet. Address TECHNIC, INC., 39 H Snow Street, Providence, R. I.

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for de-greasing — pickling
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of any size and shape —
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by
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PICKLING EQUIPMENT**

- Hairpin Hooks • Sheet Crates
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- Mechanical Bar, Tube and Coil Picklers

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HYDROSTATIC TESTING

Eliminates . . .

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- No Change in Dimension
- Corrosion Resistant
- Perfect Uniformity
- Non-Technical

The Black Oxide Finish That
Penetrates Iron & Steel Surfaces

PURITAN MANUFACTURING CO.
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METALWASH Rotary Tempering Units maintain an *extremely high air change rate*, permitting absolutely uniform temperature throughout.

METALWASH tempering units are continuous machines:

You save on labor because there are no batches to handle and re-handle.

You save on uniformity because there are no rejects—every piece of the work is exposed to the same temperature of air for the same length of time, under precisely the same conditions.

We have a representative near you who knows how to apply METALWASH uniformity to your tempering requirements. Write us today for more information.



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On any steel blackening problem
DEPEND on DU-LITE
for a Superior Finish

Here's an
example . . .



Courtesy The Poly Choke Co.

Du-Lite gave this part with its complicated knurls, slots, threads, etc. a fine rust-resistant durable black finish. It is typical of many other parts, small and large, which have been black oxidized by Du-Lite for many years. Moreover, Du-Lite meets most individual and government specifications including 57-0-2C for Type III Black Oxide finish.

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MIDDLETOWN, CONN.

Rush information on your metal finishing products.

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Company _____

Address _____

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Du-Lite

METAL FINISHING SPECIALISTS

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NARACO FINISHING TIPS

Chrome finishing for decorative hood ornaments—such as the "Rocket"—shown on this car is a plating problem . . . even to the experienced plater. NARACO's know-how in engineering has answered this problem! They have designed an efficient rack, with accurately spaced rubber bars, which produces a uniform chrome deposit free from any shading or burning.

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Specially compounded for die casting aluminum-base metal and permanent mold castings.

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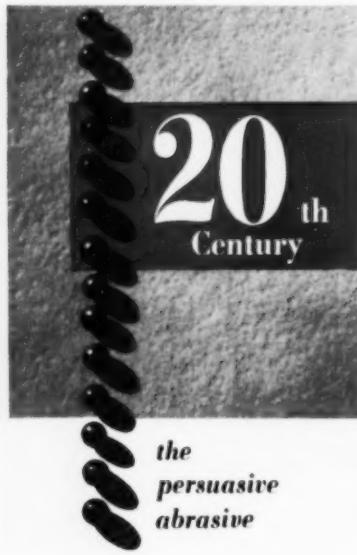
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Abrasive Wheels — Cut-off Wheels
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Custom-made for your specific material removal problems

Foundry Snagging—Billet Surfacing—Centerless Grinding

Cutting and Surfacing concrete, granite, and marble

"Moldiscs" for rotary sanders

Grinding and Finishing stainless steel welds

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Finishing Tools and Cutlery

Cutting-off—Wet or Dry Bars, Tubing, Structural, etc. Foundry Cutting—standard and reinforced wheels

Grinding Carbide Tipped Tools

Write to Abrasive Wheel Department

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MANHATTAN RUBBER DIVISION
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Whether your concern is castings, forgings or metal parts, make 20th Century *Normalized shot and grit a part of your straight-line production operation.

The high uniformity and greater durability of 20th Century *Normalized give you maximum efficiency, increased economy, and a quality product.

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One of the world's largest producers of quality shot, grit and powder—Hard Iron—Malleable (*Normalized)—Cut Wire—Cast Steel (Realsteel)
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Cut Costs With **FREE** Cutting Oil Chart

Use this free cutting oil chart as a handy guide to production costs and to more efficient machining operations.

Steel and nonferrous metals are charted with the proper cutting oil for many applications. Shows you how to use lubricants, sulphurized or compounded with extreme pressure additives, for all operations.



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EXTREME
PRESSURE
LUBRICATION
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The new miracle—multi-purpose molybdenum disulfide lubricant.

Anti-Seize is a stable non-melting lubricant having a phenomenal capacity to prevent seizing and galling at bearing pressures well over 100,000 pounds per square inch. Anti-Seize will lubricate at temperatures below sub-zero and up to 750 degrees F.

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complete story



MANUFACTURERS OF THE MOST COMPLETE LINE
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MADISON, NEW JERSEY

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ALUMINUM
EXTRUSIONS**
made to your
SPECIFICATIONS

QUALITY
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Extrusions Since
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Prove to your own satisfaction that the MOLYKOTE line of industrial lubricants is one of the most spectacular contributions to metal progress in many decades. Send for free literature today . . . and then order a trial supply.

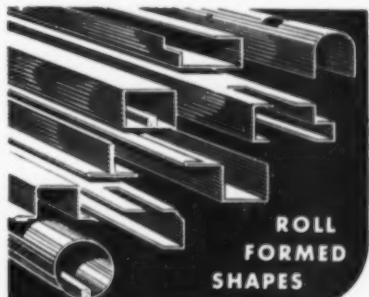
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AUTOMATIC WELDING
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METAL PROGRESS; PAGE 62

FROM BLANK TO FINISHED PART IN ONE OPERATION by SCHNELL PROCESS of Deep Draw Dies

On half tank sections formerly requiring three drawings and two annealing operations with scrap running as high as 50%!! The Schnell process reduced scrap loss to 1% or less . . . and production increased tremendously. Other advantages include better metallurgical properties, less metal distortion and a more uniform wall thick-

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SCHNELL
TOOL & DIE CORP.

SALEM, OHIO

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USE OUR
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*Powder Metallurgy
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IN 10 SECONDS!**



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Complete Arc Welding Accessories
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your comprehensive independent
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Tubes • Rods • Shapes • Bars
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Sales Office
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**RESIDUAL STRESS
MEASUREMENTS**

This volume, written by four outstanding authorities, devotes 204 pages to the important problem of the nature and extent of residual or "internal" stresses in metals and metal parts prior to actual structural or operating use.

How to measure residual stresses . . . The state of stresses produced in metals by various processes . . . Relief and redistribution of residual stresses in metals . . . How residual stresses originate, their nature and their effect on metals.

204 pages, \$4.50

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7301 Euclid Ave. Cleveland 3

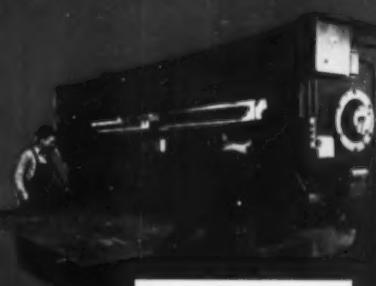
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Steelweld machines have an enviable reputation throughout the United States and the world for their ease of operation and low-maintenance performance. Complete line for metal from light gauge to 1 1/4" and lengths to 24'-0". Representatives in all principal cities.



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Wickliffe, Ohio

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TITANIUM • BRONZES • ALUMINUM
COPPERWELD • SILVER PLATED WIRES
OTHER NON-FERROUS

ROUND WIRE FLAT
for
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* ELECTRONICS
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LITTLE FALLS ALLOYS

INCORPORATED
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ALL TYPES OF STAINLESS STEEL
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BOLTS & CAP SCREWS
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ask SESSIONS
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STAMPED ASSEMBLIES
SAVE TIME & MONEY

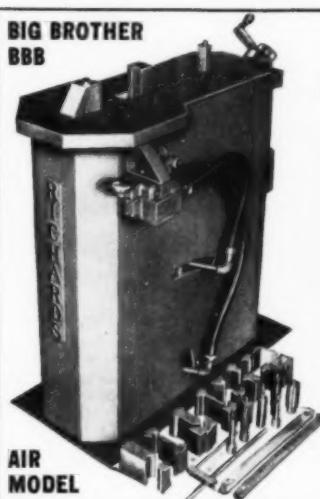
Send samples
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on special
stampings and
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SESSIONS
SON

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BIG BROTHER
BBB



Multiform Benders Produce Without Special Tooling

• SAVE ON SET UP TIME

• REDUCE PRODUCTION TIME

• ELIMINATE SPECIAL TOOLING

• FOR BENDING ALL KINDS OF MATERIAL

UP TO 1/4" x 4"

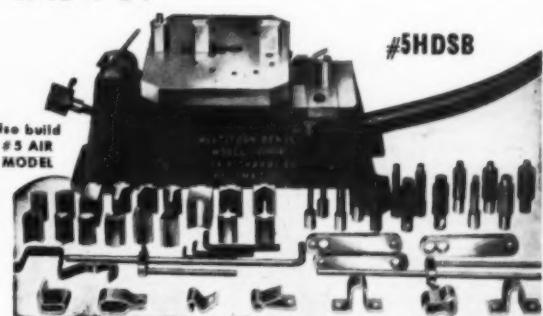


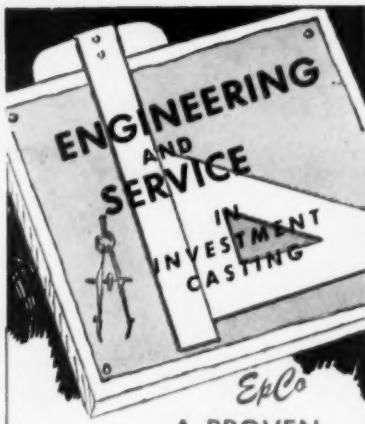
Illustrated above are a few of the many forms that can be produced efficiently on the Multiform Bender, using the standard tooling.

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FULL INFORMATION

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CASTINGS IN FERROUS AND
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STAINLESS STEEL PART for milk
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from solid stock.
Only finish operations required
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HOW TO SAVE MONEY WITH GRC SMALL DIE CASTINGS

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for designers and engineers; case
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Write today for this bulletin.

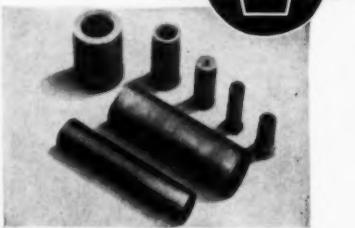
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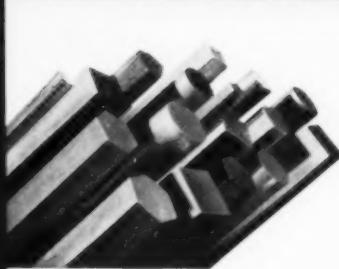
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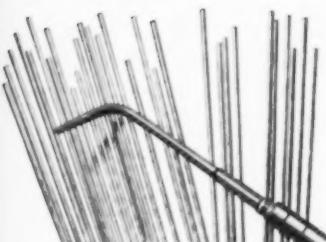
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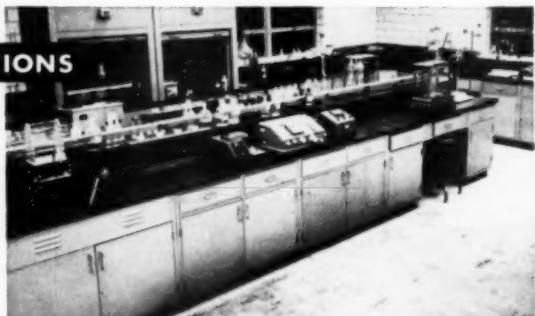
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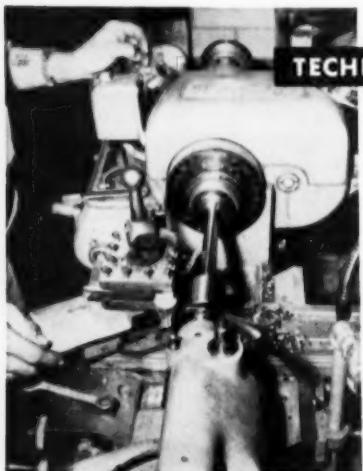


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TABLE OF CONTENTS

DATA SHEETS

- #1 - MACDERMID METAL FINISHING COMPOUNDS
- #2 - DYCLENE "E" - Reverse Current Cleaner for Die Castings
- #3 - ANODEX 6IX - For Cleaning Buffed Copper
- #4 - ANODEX - Reverse Current Cleaner for Steel
- #5 - ROCHELTEX - For Copper Plating
- MACDERMID BRIGHT COPPER PLATING PROCESS
- #6 - CHROME RESISTEX - For Cleaning Prior to Chrome Plating
- #7 - PRESSURE SPRAY WASHING MACHINE CLEANERS
- #8 - CHROMETEX - Nickel Activator
- #9 - METEX ACID ADDITIVE
- #10 - METEX ZINC STRIPPER
- #11 - METEX DURAFOS - Phosphate Coating
- #12 - METEX PLASTIC STRIPPER
- #13 - THE ALUMETEX PROCESS - For Electroplating on Aluminum
- #14 - TROXIDE - Dry Acid Pickling Salt
- #15 - BLACKMAX SALTS - Black Oxidizing Salts for Steel
- #17 - CHROMEFOOME - For Reducing Acid Mists
- #20 - METEX DB ACID ELECTROLYTIC STRIP
- #21 - MACDERMID ALUMINUM BRIGHT DIP
- #23 - SOLVENT EMULSION CLEANERS
- #24 - COMPOUNDS FOR FINISHING ALUMINUM
- #25 - DEOXIDEX - For Cleaning Aluminum for Spot Welding
- #26 - MIRROCU - Chemical Copper Polish
- #27 - PHOSPHOTEX - Zinc Phosphate Process
- #28 - METEX FILTER POWDER
- #29 - METEX PAINT STRIPPER T-19
- #30 - METEX STRIP AID - For Immersion Stripping of Copper and Nickel
- #31 - METEX 157 - Phosphoric Acid Cleaner
- #32 - MIRROFE - Chemical Steel Polish
- #33 - METEX M-600 - Alkaline Smut Remover and De-ruster

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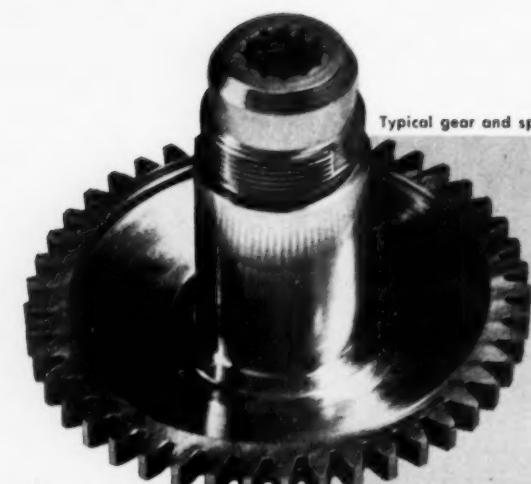
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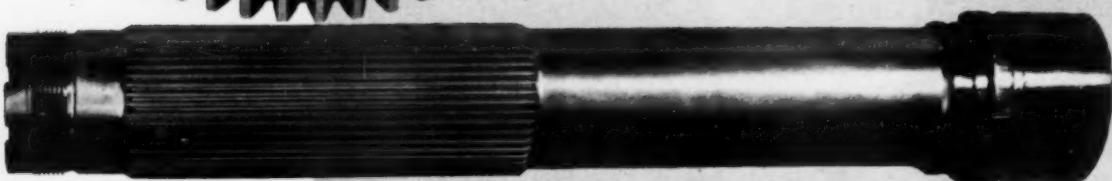
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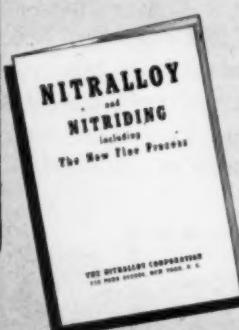
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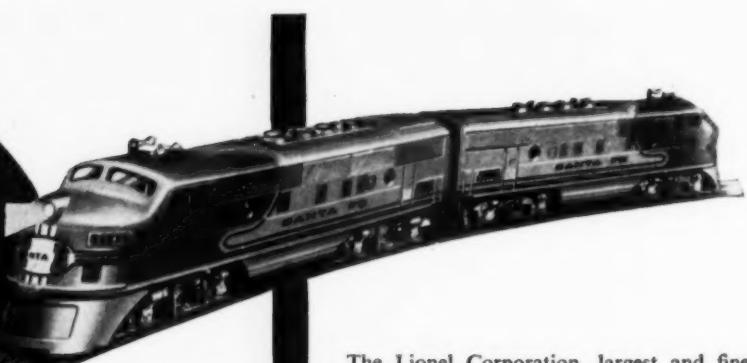
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AM-28

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to build...so*



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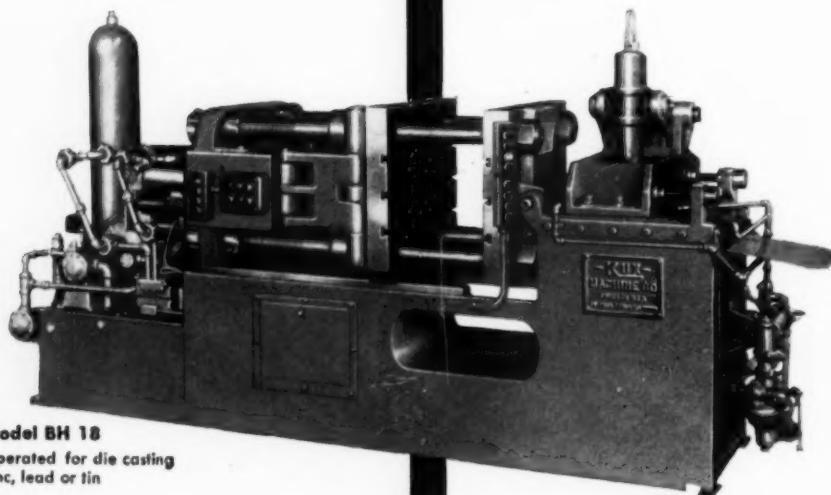
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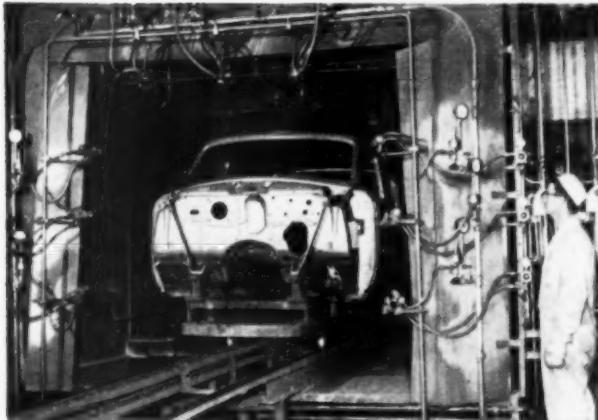
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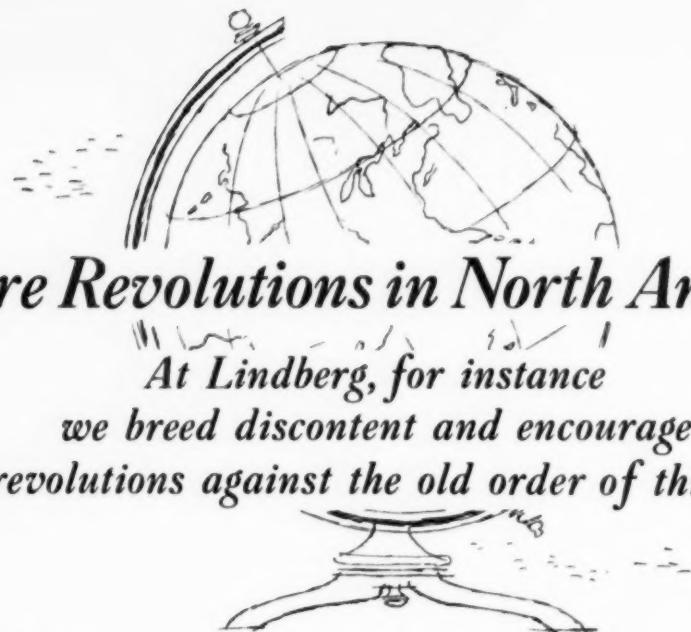
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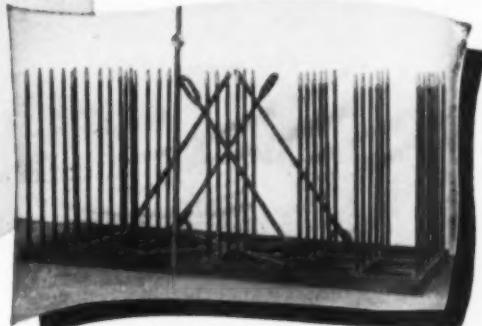
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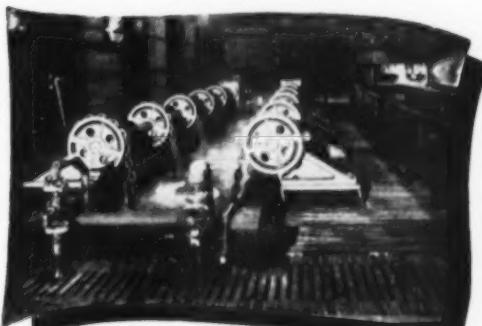
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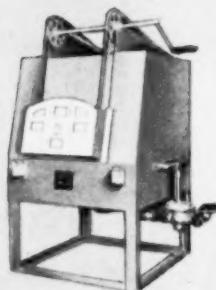
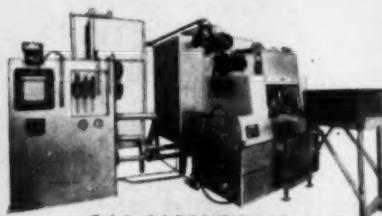
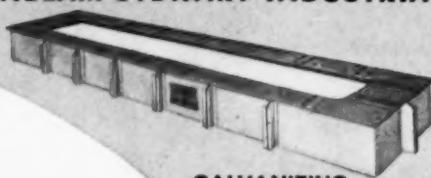
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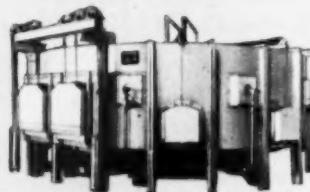
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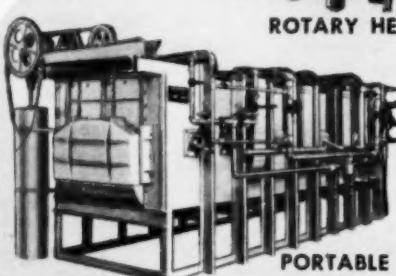
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WOOD BAND SAWS



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Each of these applications demands its own special combination of high fatigue life, fine surface finish, accurate and uniform size and special physical properties. In every case, one of Sandvik's wide variety of steels fits the requirements to a "T".

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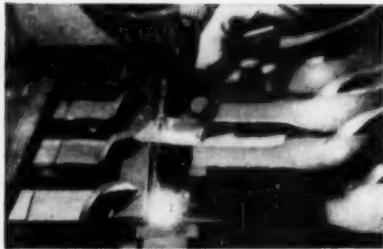
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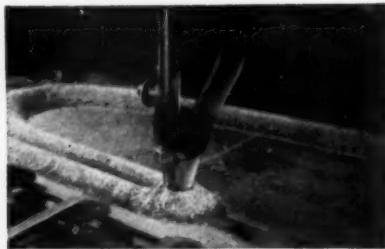


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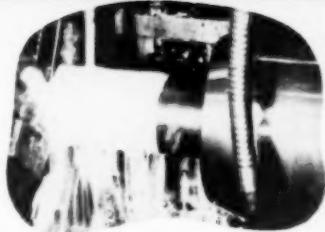
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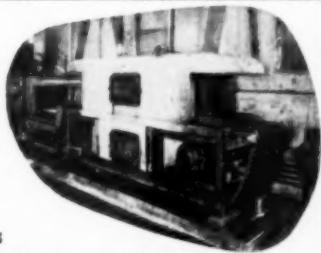
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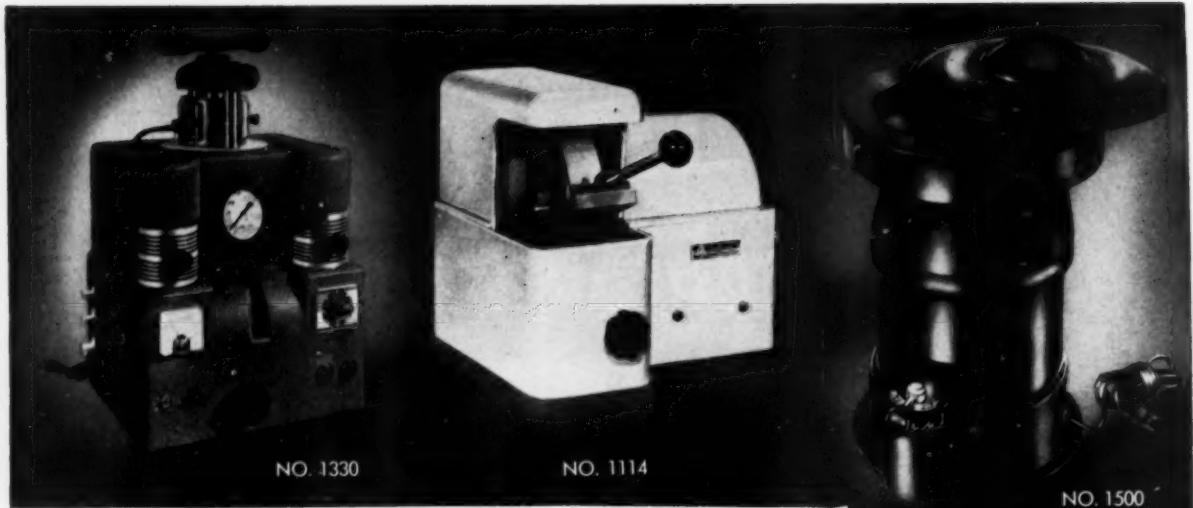


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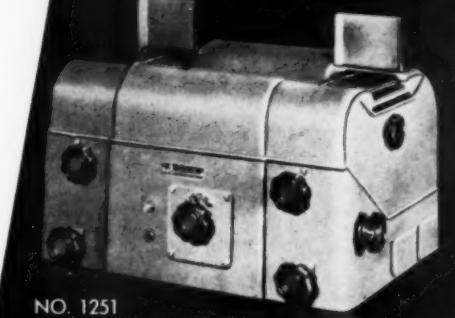
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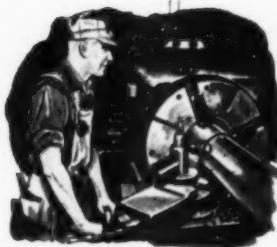


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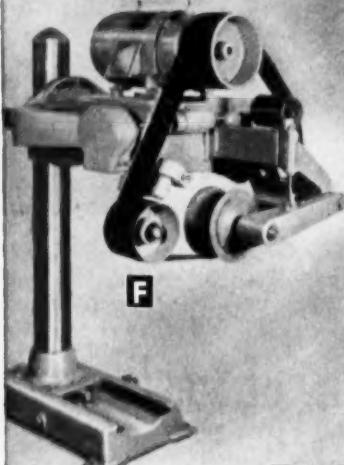
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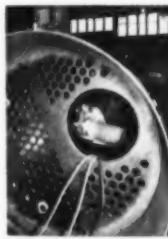
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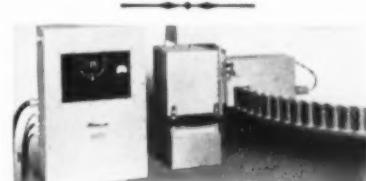
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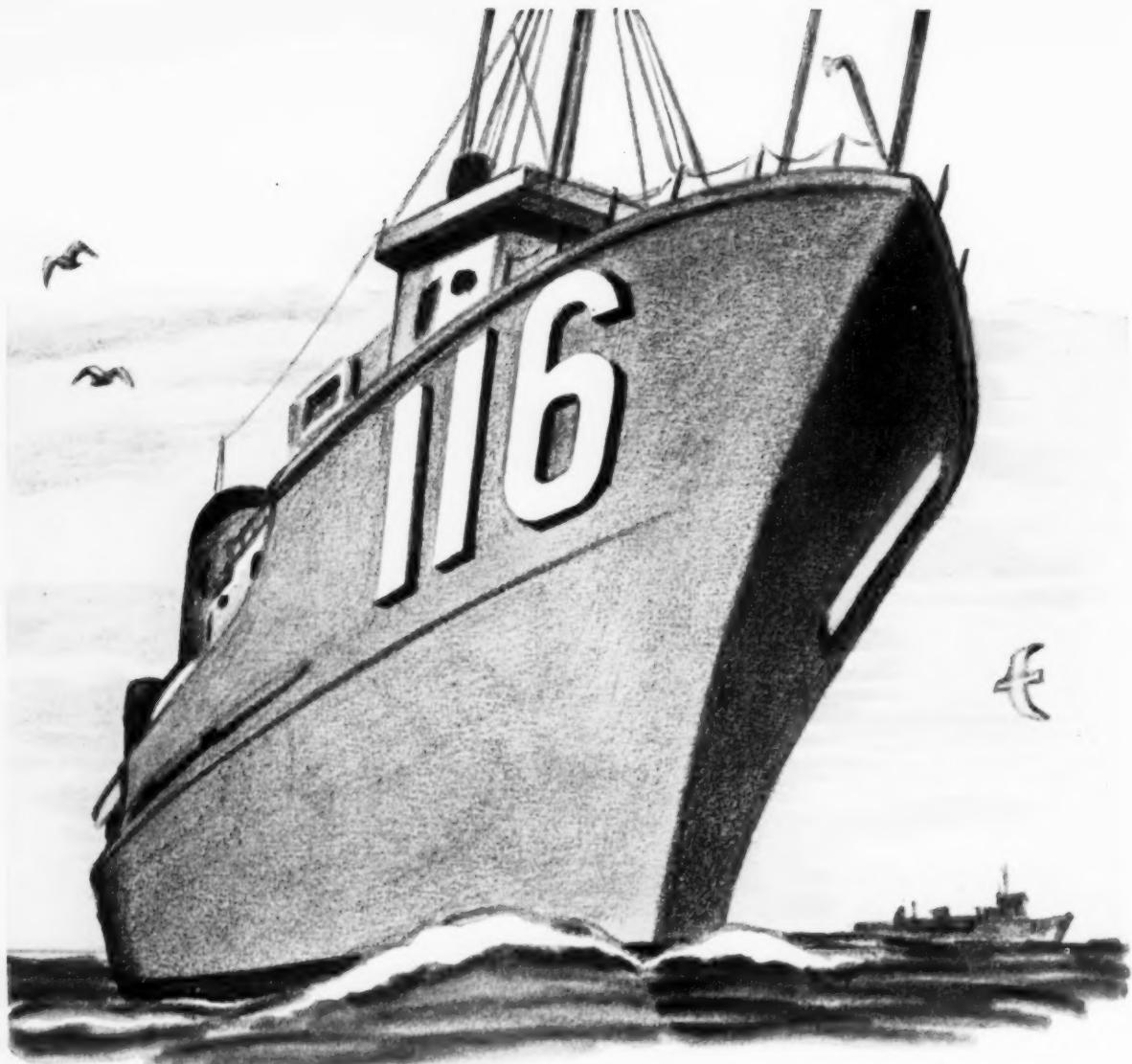
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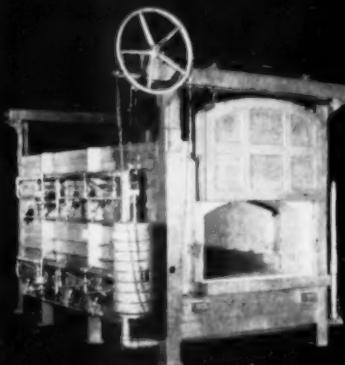
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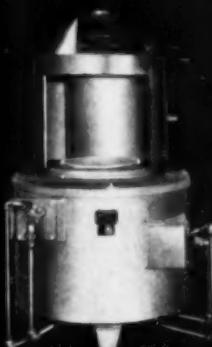
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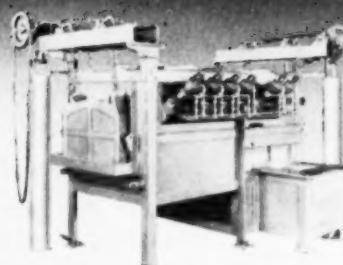
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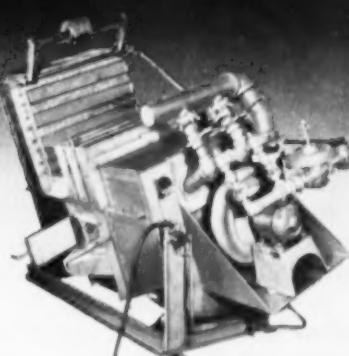
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Because of its antifriction qualities, resistance to corrosion, conformability, and good embedding characteristics, tin is invaluable in bearing metals. Without tin-base or tin alloy

bearings, the wheels of industry could not turn so smoothly and efficiently.

And Straits Tin is not only one of our most useful metals. It is now fast becoming one of our most valued chemicals. Tin in chemical compounds — stabilizers, opacifiers, antioxidants, preservatives — is contributing greatly in the competitive race for improvement in products from plastics and the new chlorinated rubber paints to ceramics, sensitized paper — now even jute bags.

Take a New Look at Straits Tin

Over one-third of the world's tin is mined and smelted in Malaya. Known as Straits Tin, this metal is over 99.87% pure, and is world-famous for its absolute reliability of grade.

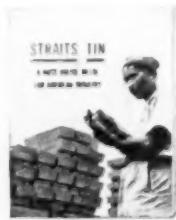
Today new uses for Straits Tin are making it more valuable than ever to American industry. And continuing research will, in the near future, find still more ways in which Straits Tin can serve you. Whether you're planning a new product, improving an old one, or seeking ways to avoid the squeeze between rising costs and resistance to higher product prices, a careful reappraisal of the properties of Straits Tin may uncover a profitable answer to your problem.



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FOREWORD

THIS is the First Supplement to the 1948 edition of the Metals Handbook and will greatly increase the serviceability of the original volume, which has won such an enviable place in the metal world.

The members of the Metals Handbook Committee have studied the 1948 edition and selected the sections in which the greatest advancement has been made and have determined the desirability of presenting new and additional material and information in this Supplement.

After these sections were determined and a survey made of the latest advances, 22 author committees were appointed by the main committee, and for the past year, under the direction of Taylor Lyman, Editor of the Metals Handbook, and Carl H. Gerlach, ASM Staff Engineer, these capable and conscientious committeemen have been giving their time and assistance in compiling the technical information for this volume.

It has been by the faithful work and cooperation of the members and others that the Society has been able to make the progress it has in the production of this world-recognized volume of the Metals Handbook.

The Board of Trustees wishes to take this opportunity to express its most sincere appreciation to all the committeemen and members of the ASM who have so graciously contributed to the assembly of the information contained in the reports of the various committees.

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The Selection of Constructional Steels

By the ASM Committee on Carbon and Alloy Steels

THE steels considered here are those carbon and alloy steels used in the general construction of machinery, both stationary and mobile. Excluded are steels with special properties, frequently highly alloyed, such as tool steels, steels for electrical or magnetic purposes, steels for service at extremely low or high temperature and for corrosion resistance.

A steel for any particular use is properly selected when the result is a part that will satisfy the engineering use at the lowest final cost. Many factors enter into such a selection, principally the mechanical and physical properties required to satisfy the engineering use, the cost of processing, the processing equipment required and its availability, and the cost and availability of the steel. Since these factors vary widely, the correct choice of steel for any set of conditions is the one that provides the best balance among all the factors. Thus, a categorical selection of steel for a certain type of part is impractical. The successful use throughout industry of different steels for similar parts is ample evidence of the complexity of the problem.

Engineering Considerations

The properties required to meet engineering use are always the first consideration because this need immediately determines an important part of the final cost. The basic problem is to find the steel that has the required minimum mechanical and physical properties that will give satisfactory service; the load-carrying ability and the shock, abrasion and corrosion resistance of the steel must be matched with the service requirements of the part, multiplied by a reasonable factor of safety. Seldom are all the properties of a material of equal importance in any one application. The problem consists of determining which of the properties are important and then selecting the material that provides those properties at the lowest final cost. In addition to having the required favorable properties, the steel must be free from *unfavorable* properties that would preclude its use.

In determining the properties required, a reasonably accurate knowl-

Major Subdivisions	Page
Engineering Considerations	1
Fatigue	1
Brittle Failures	2
Hot Rolled Steels	3
Cold Drawn Steels	3
Low-Alloy Steels	4
Hardenable Steels	4
Selection Procedure	10
Similarity of Tensile Properties	12
Steels for Case Hardening	13
Availability of Steels	14
Plant Standardization of Steels	14
Hardenability Bands for H-Steels	16

edge of the service conditions, obtained from design calculations, from past experience or from actual test of the apparatus, is essential. Best of all is a combination of information from all these sources.

When considering mechanical requirements, attention should be directed first to the type of loading. If it is static or if the frequency of load application during the expected life is so low that fatigue can be neglected, then the governing property is the yield strength for all ordinary applications. For those rare applications where no permanent deformation whatever is allowable, design must be based on the more precisely determined proportional limit, which is always lower than the yield strength. The parts where yield strength and proportional limit apply are usually static parts in static machines.

The stresses resulting from the known static loads can be computed from the relationship between load and section modulus, and the steel can be

selected from a consideration of the strength-weight ratio desired in the design and from the yield strength of steels. To this must be added judicious allowances for overloads—that is, a factor of safety. This completes the selection so far as calculations are concerned and is usually as far as the process can be carried if only one or a few parts are to be made. A conservative approach is the rule, because there is no opportunity for further refinements. Design and selection so based often fall short, either because of excessive weight (overdesign) or insufficient strength (underdesign). Previous experience with something similar often yields valuable information, and prudent engineers always draw upon such experience whenever it is available, so as to refine a design or material selection beyond the possibilities of calculation alone.

Fatigue

Even in parts designed for predominantly static loading, the engineer must be alert to conditions in which external cyclic loading, of even a small number of cycles, may produce a fatigue problem. Such problems arise when the part is designed with a low section modulus in the direction of maximum stress. Under these conditions the part experiences high flexure under load and may fail from fatigue after no more than a few hundred cycles. Such failures arise most frequently when soft (not heat treated) steels are used. Here the fatigue limit approaches the yield strength. If the part is designed statically with a low factor of safety there will be an equally low factor of safety in fatigue. Because of stress raisers, a dynamic load can easily exceed the fatigue limit. If applied often enough, the dynamic load will cause fatigue failure.

When the loading is predominantly dynamic, fatigue resistance of the part becomes the primary consideration. All known cyclic stresses must be totaled and the total appraised. Unfortunately, the loads are usually difficult, and frequently impossible, to determine with even reasonable accuracy. Furthermore, the effect of sudden changes of section of any kind (stress

Supplements those sections of the 1948 Metals Handbook relating to alloy steel (pages 453 to 488) and hardenability (pages 489 to 502)

raisers) is so great that accurate mathematical evaluation is difficult. This is an important difference between static and dynamic applications. Finally, the fatigue limits of steels cannot be determined so precisely as the other mechanical properties. The fact that most failures of dynamically loaded parts are from fatigue is ample evidence that, in spite of the attention given this phase of design, it remains an area of many uncertainties.

The risk is minimized, first, by drawing on past experience and, second, by testing experimental models. Such testing, in either laboratory or field, is used to prove the design and material selection and to obtain refinements beyond the possibilities of calculations alone. Products scheduled for high production are almost invariably so tested, because of the high cost of correcting poor design or material selection after the part is in production. The modern passenger automobile or truck would be impossible without such testing. The process is being applied vigorously to more products as time goes on, and the importance of adequate life testing of both parts and complete machines under actual conditions of operation cannot be overemphasized.

The fatigue limit of steels, both wrought and cast, may be determined directly by well established laboratory test methods (page 118, 1948 Handbook), and a sufficient amount of such testing has been done to establish the fundamental behavior of steels in various conditions. It has been found that the fatigue limit of steel is more closely related to the tensile strength than to any other property. The ratio of fatigue limit to tensile strength varies with the condition of the steel, being about 50% for unhardened steels and about 45% for hardened steels. The ratio drops slowly as hardness increases but, more important, the sensitivity to stress raisers increases as hardness rises (see "Stress Concentration", page 97). It is because of these variations that most tables of mechanical properties of steels do not list fatigue limits.

Although fatigue data indicate correctly what the *steel* will do in a laboratory testing machine, they do not indicate what the *part* will do in service when made of that steel unless the part has the same careful design and surface finish as the fatigue test specimen. Since such conditions are rare, a suitable steel often gives a poor performance because of poor design or finish of the part, often both. In practical terms this means that the most suitable fatigue test specimen is the part itself under actual or realistically simulated operating conditions. When failures result, the proper order of consideration is: first, finish; second, design and, last, material. The material is often the easiest to change, and engineers too frequently specify costly, high-strength materials with indifferent success when a rational change in finish or design or both would completely correct the trouble at less cost and might even permit the use of a less costly material than originally selected. An excellent practical reference on this subject is "Prevention of Fatigue in Metal Parts", by the staff of Battelle Memorial Institute, John Wiley & Sons (1941).

Brittle Failures

The next consideration from an engineering standpoint is insurance against brittle failure. Complete absence of failure is always desired but if failure must come, then ductile failure with its prior warning, as by bending or twisting, is much to be desired over brittle failure, which occurs without warning. Brittle failure may occur under substantially static conditions (low strain rate) or under shock (high strain rate). In spite of much laboratory testing of notched bars, there are

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rarely any quantitative values which have been established as unsafe for a particular service.

Calculations provide almost no help whatever. Actual parts or structures should be tested under actual or closely simulated service conditions wherever possible. For most usual applications, the commonly used steels have adequate toughness and selection is made accordingly. Only the exceptional applications require special attention—for instance, service at subzero temperatures, extremely high strain rate such as ballistic shock, or structures in which there is a high degree of restraint, as in some weldments. Of these, only the last is within the scope of this article.

Conventional tension testing provides no dependable measure of this behavior of steels. Percentage elongation and reduction of area are often considered an indirect measure of toughness at low strain rate. Actually they are measures of ductility, which is one of the aspects of steel quality. These values may be an indication of toughness of the part when the stress is uniaxial but when the stress system is more complex their usefulness for this purpose disappears. These values appear in specifications as measures of steel quality, as a result of accumulated experience to the effect that, in a particular application, steel possessing certain minimum values for ductility has been found satisfactory. This type of information is not, however, a specification for toughness for that service.

Toughness at higher strain rates, usually called shock resistance or impact resistance, is most often measured by one of the notched-bar tests, discussed in the article on page 112 of the 1948 Handbook. The section in that article on interpretation of results should be kept clearly in mind when selecting a steel for service involving shock; the gist of it is: there is no generally established relationship between notched-bar test values and the minimum requirements for any particular service. It obviously follows that such test values properly appear in specifications only when the specific needs of a particular service have been established.

An example of this lack of relationship can be found in the leaves of an automobile rear spring. The spring must withstand shock and one might assume that the leaves must have high notch toughness. Actually the hardness is about 400 Brinell and the notch toughness about 10 ft-lb, a normal value for that hardness but still low for energy absorption in a test bar. The ability of the spring to resist shock is provided in the design, and notch toughness for the steels normally used is not a controlling factor, even though the loading is primarily one of shock.

The true significance of tests conducted at high strain rate lies in their ability to demonstrate the degree to which metal can deform under service conditions. If it can deform enough to fail with a tough fracture it will absorb more energy—that is, withstand heavier shock—than if it fails with a brittle fracture. To the variables affecting this behavior (metallurgical history of the material and service temperature, as discussed on page 112 of the 1948 Handbook) should be added a design consideration, the degree of restraint in the structure.

If a series of notched-bar tests is run on a steel at different temperatures, it will be found that within a relatively narrow temperature range the fracture will change from tough to brittle as the temperature falls. In this range, the energy absorbed in breaking the bar will drop as much as 80% (Fig. 1). This transition temperature range is affected by many factors: Killed steels show lower transition temperatures than semikilled or rimmed steels; in low-carbon steels, not heat treated, a minimum manganese content is helpful in preventing high transition temperatures. Normalized steel is superior to hot rolled. Best

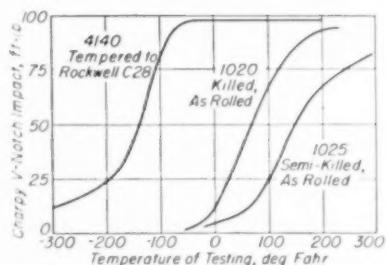


Fig. 1. Impact Curves Showing Transition from Ductile to Brittle Fracture for Three Steels. (1) 4140, tempered martensite, Rockwell C 28; (2) Fully-killed 1020, as rolled; (3) Semi-killed 1025, as rolled

Table I. Composition Limits of Carbon Steels

(Applicable only to semi-finished products for forging, hot rolled and cold finished bars, wire rods and seamless tubing)

AISI No.	C	Mn	P (max)	S (max)	SAE No.
Basic Open Hearth and Acid Bessemer Carbon Steels^(a)					
C1006	0.08 max	0.25 to 0.40	0.040	0.050	1006
C1008	0.10 max	0.25 to 0.50	0.040	0.050	1008
C1010	0.08 to 0.13	0.30 to 0.60	0.040	0.050	1010
C1011	0.08 to 0.13	0.60 to 0.90	0.040	0.050	....
C1012	0.10 to 0.15	0.30 to 0.60	0.040	0.050	....
C1015	0.13 to 0.18	0.30 to 0.60	0.040	0.050	1015
C1016	0.13 to 0.18	0.60 to 0.90	0.040	0.050	1016
C1017	0.15 to 0.20	0.30 to 0.60	0.040	0.050	1017
C1018	0.15 to 0.20	0.60 to 0.90	0.040	0.050	1018
C1019	0.15 to 0.20	0.70 to 1.00	0.040	0.050	1019
C1020	0.18 to 0.23	0.30 to 0.60	0.040	0.050	1020
C1021	0.18 to 0.23	0.60 to 0.90	0.040	0.050	1021
C1022	0.18 to 0.23	0.70 to 1.00	0.040	0.050	1022
C1023	0.20 to 0.25	0.30 to 0.60	0.040	0.050	....
C1024	0.19 to 0.25	1.35 to 1.65	0.040	0.050	1024
C1025	0.22 to 0.28	0.30 to 0.60	0.040	0.050	1025
C1026	0.22 to 0.28	0.60 to 0.90	0.040	0.050	1026
C1027	0.22 to 0.29	1.20 to 1.50	0.040	0.050	1027
C1029	0.25 to 0.31	0.60 to 0.90	0.040	0.050	....
C1030	0.28 to 0.34	0.60 to 0.90	0.040	0.050	1030
C1032	0.30 to 0.36	0.60 to 0.90	0.040	0.050	....
C1033	0.30 to 0.36	0.70 to 1.00	0.040	0.050	1033
C1035	0.32 to 0.38	0.60 to 0.90	0.040	0.050	1035
C1036	0.30 to 0.37	1.20 to 1.50	0.040	0.050	1036
C1037	0.32 to 0.38	0.70 to 1.00	0.040	0.050	....
C1038	0.35 to 0.42	0.60 to 0.90	0.040	0.050	1038
C1039	0.37 to 0.44	0.70 to 1.00	0.040	0.050	1039
C1040	0.37 to 0.44	0.60 to 0.90	0.040	0.050	1040
C1041	0.36 to 0.44	1.35 to 1.65	0.040	0.050	1041
C1042	0.40 to 0.47	0.60 to 0.90	0.040	0.050	1042
C1043	0.40 to 0.47	0.70 to 1.00	0.040	0.050	1043
C1045	0.43 to 0.50	0.60 to 0.90	0.040	0.050	1045
C1046	0.43 to 0.50	0.70 to 1.00	0.040	0.050	1046
C1049	0.46 to 0.53	0.60 to 0.90	0.040	0.050	1049
C1050	0.48 to 0.55	0.60 to 0.90	0.040	0.050	1050
C1052	0.47 to 0.55	1.20 to 1.50	0.040	0.050	1052
C1053	0.48 to 0.55	0.70 to 1.00	0.040	0.050	....
C1055	0.50 to 0.60	0.60 to 0.90	0.040	0.050	1055
C1060	0.55 to 0.65	0.60 to 0.90	0.040	0.050	1060
C1065	0.60 to 0.70	0.60 to 0.90	0.040	0.050	1065
C1069	0.65 to 0.75	0.40 to 0.70	0.040	0.050	....
C1070	0.65 to 0.75	0.60 to 0.90	0.040	0.050	1070
C1072	0.65 to 0.76	1.00 to 1.30	0.040	0.050	....
C1075	0.70 to 0.80	0.40 to 0.70	0.040	0.050	....
C1078	0.72 to 0.85	0.30 to 0.60	0.040	0.050	1078
C1080	0.75 to 0.88	0.60 to 0.90	0.040	0.050	1080
C1084	0.80 to 0.93	0.60 to 0.90	0.040	0.050	....
C1085	0.80 to 0.93	0.70 to 1.00	0.040	0.050	1085
C1086	0.82 to 0.95	0.30 to 0.50	0.040	0.050	1086
C1090	0.85 to 0.98	0.60 to 0.90	0.040	0.050	1090
C1095	0.90 to 1.03	0.30 to 0.50	0.040	0.050	1095
B1010	0.13 max	0.30 to 0.60	0.07 to 0.12	0.060	....
Basic Open Hearth Resulfurized Carbon Steels^(b)					
C1108	0.08 to 0.13	0.50 to 0.80	0.040	0.08 to 0.13	....
C1109	0.08 to 0.13	0.60 to 0.90	0.040	0.08 to 0.13	1109
C1110	0.08 to 0.13	0.30 to 0.60	0.040	0.08 to 0.13	....
C1113	0.10 to 0.16	1.00 to 1.30	0.040	0.24 to 0.33	....
C1115	0.13 to 0.18	0.60 to 0.90	0.040	0.08 to 0.13	1115
C1116	0.14 to 0.20	1.10 to 1.40	0.040	0.16 to 0.23	1116
C1117	0.14 to 0.20	1.00 to 1.30	0.040	0.08 to 0.13	1117
C1118	0.14 to 0.20	1.30 to 1.60	0.040	0.08 to 0.13	1118
C1119	0.14 to 0.20	1.00 to 1.30	0.040	0.24 to 0.33	1119
C1120	0.18 to 0.23	0.70 to 1.00	0.040	0.08 to 0.13	1120
C1125	0.22 to 0.28	0.60 to 0.90	0.040	0.08 to 0.13	....
C1132	0.27 to 0.34	1.35 to 1.65	0.040	0.08 to 0.13	1132
C1137	0.32 to 0.39	1.35 to 1.65	0.040	0.08 to 0.13	1137
C1138	0.34 to 0.40	0.70 to 1.00	0.040	0.08 to 0.13	1138
C1140	0.37 to 0.44	0.70 to 1.00	0.040	0.08 to 0.13	1140
C1141	0.37 to 0.45	1.35 to 1.65	0.040	0.08 to 0.13	1141
C1144	0.40 to 0.48	1.35 to 1.65	0.040	0.24 to 0.33	1144
C1145	0.42 to 0.49	0.70 to 1.00	0.040	0.04 to 0.07	1145
C1146	0.42 to 0.49	0.70 to 1.00	0.040	0.08 to 0.13	1146
C1148	0.45 to 0.52	0.70 to 1.00	0.040	0.04 to 0.07	....
C1151	0.48 to 0.55	0.70 to 1.00	0.040	0.08 to 0.13	1151
Basic Open Hearth Reporphorized and Resulfurized Carbon Steels^(c)					
C1211	0.13 max	0.60 to 0.90	0.07 to 0.12	0.08 to 0.15	....
C1212	0.13 max	0.70 to 1.00	0.07 to 0.12	0.16 to 0.23	....
C1213	0.13 max	0.70 to 1.00	0.07 to 0.12	0.24 to 0.33	....
Acid Bessemer Resulfurized Carbon Steels^(d)					
B1111	0.13 max	0.60 to 0.90	0.07 to 0.12	0.08 to 0.15	1111
B1112	0.13 max	0.70 to 1.00	0.07 to 0.12	0.16 to 0.23	1112
B1113	0.13 max	0.70 to 1.00	0.07 to 0.12	0.24 to 0.33	1113

(a) Basic open hearth carbon steels: When silicon is required the following ranges are commonly used—up to grade C1015, exclusive, 0.10% max; grades C1015 to C1025, inclusive, 0.10% max, or 0.10 to 0.20%, or 0.15 to 0.30%. If required, copper may be specified as an added element.

(b) Basic open hearth resulfurized carbon steels: When silicon is required the following ranges are commonly used—up to C1113, exclusive, 0.10% max; C1113 and over, 0.10% max, or 0.10 to 0.20%, or 0.15 to 0.30%.

(c) Basic open hearth rephosphorized and resulfurized carbon steels: It is not common practice to specify silicon limits.

(d) Acid bessemer resulfurized carbon steels are not produced to specified silicon content. (Silicon is normally very low—0.01 to 0.02%).

values are obtained from steels fully quenched and tempered.

Increasing degree of restraint in a structure can change the fracture from tough to brittle. As loading changes from axial through bi-axial to tri-axial, a steel may, at constant temperature, show a change from tough to brittle behavior. The increasing use of welded construction with its many opportunities for producing multi-directional stress points up the necessity for considering this factor in steel selection. Where it can be used, stress relief after welding is helpful. Otherwise, the type of steel or the design must be changed.

Because of the wide differences in the notch toughness of steel and the occasional spectacular failures that result from lack of it, it is too easy to conclude that a high value for notch toughness is necessary when steels are subject to shock loading. It is often expensive to provide this property in addition to the others required, especially if the part is large. A careful look at many parts in everyday use will show that, for all except the unusual application, the commonly used steels have adequate shock resistance. Only where this is known not to be true is there need for special attention to high notch-toughness and in these the design should be carefully reviewed and, if possible, altered to distribute stress more uniformly. It is almost an axiom that when attempts are made to correct poor design with metallurgy alone the results are expensive and often disappointing.

Hot Rolled Steels

Carbon steel as rolled or as forged is the lowest cost steel, and in the many applications where the properties are satisfactory, it should be used. Table I gives composition limits of hot rolled carbon steel bars; properties normally expected in sections of 1-in. diam are tabulated on page 5; both regular and free-cutting grades, in both the hot rolled and cold drawn conditions, are included. The table shows a wide range—from 24,000 to 67,000 psi yield strength in the hot rolled condition.

Many builders of machinery, notably the farm equipment industry, take advantage of these low-cost steels by designing many major components specifically for them. Often the workability of the low-carbon steels is essential to successful manufacture of parts. Examples are the many components formed and drawn from flat rolled steels and the immense use of cold heading, which successfully utilizes both low-carbon and medium-carbon grades. The decreased machinability of the unannealed hot rolled grades with carbon content higher than in 1050 usually limits their use in the as-rolled condition to parts requiring little or no machining.

Cold Drawn Steels

Cold drawn steels come next in order of increased strength. The low-cost drawing process enhances the hardness, tensile strength and especially the yield strength. In hot rolled steel the ratio of yield strength to tensile strength is about 55%, whereas in cold drawn steel it is about 85%. Thus, by using a cold drawn steel where it fits, the designer

can improve the strength-weight ratio and thereby reduce costs and save weight when necessary. By special practice, the tensile strength and yield strength of the medium-carbon grades, cold drawn, can be made equivalent to those of heat treated steel of 240 Brinell, and such cold drawn steels are successfully used in many important applications to eliminate not only the cost of heat treatment but also, more important, the inevitable straightening costs which may be the largest single item in labor cost.

Figure 2 shows the change in mechanical properties with increase in cold reduction by drawing. The increase in strength is accompanied by a decrease in elongation and reduction of area, but these values are still sufficient for most applications.

In recent years a further development in cold drawing has been the use of heavier drafts on selected grades, usually from 1035 to 1050 and similar carbon contents in the free-cutting steels. The heavy draft increases the tensile strength and yield strength, as shown in Fig. 2, and when cold drawing is followed by stress relieving, usu-

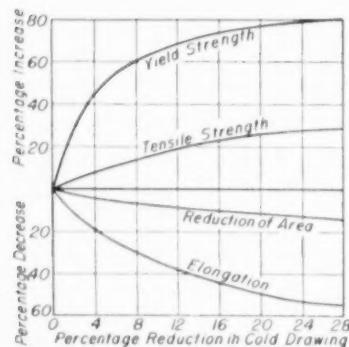


Fig. 2. Effect of Cold Drawing on the Tensile Properties of Steel. For bars up to 1-in. cross section, having tensile strength of 110,000 psi or less before drawing (Bethlehem Steel)

ally between 700 and 1050 F, minimum yield strength as high as 100,000 psi and tensile strength of 120,000 psi can be guaranteed, with satisfactory toughness. This process is sensitive to both size and composition, particularly carbon and manganese. No generally accepted specifications have been adopted; however, numerous private specifications are in use, and the practical limits are known.

For the higher-strength cold drawn bars, no steel of carbon content higher than 1050 is shown in the table on the next page, although, hot rolled, the higher-carbon steels are stronger. Such steels are produced as specialties: Bars must be annealed before cold drawing, thus increasing the cost; the increase in strength from drawing becomes proportionately less as the strength of the base steel rises; and the decrease in ductility from drawing, subtracted from the already lower ductility due to higher carbon content, makes the ductility of the product somewhat lower than desirable; also, these steels do not machine readily without annealing, which destroys the properties produced by cold drawing.

In considering the mechanical properties of cold drawn steels, a sharp distinction must be made among various "cold finishing" processes. The steels considered here are those produced by cold drawing an oversize hot rolled bar through a die; the resulting cold work is responsible for the improvement in properties. Because of power limitations, the maximum size bar that can be drawn is about 3-in. diam. Bars can also be cold finished by turning, turning and polishing, or turning and grinding. Sizes larger than 3 in. are always so finished and smaller sizes may be. Since no cold work is done except a small amount from pressure of cutting tools, the steels so processed are no stronger than hot rolled steels.

There are additional processing advantages in the use of cold finished steels, drawn or turned. One is close dimensional control. Table II shows the size tolerances for commercial bars as furnished by the mill. Often no further machining will be needed. Another advantage is that odd sizes can be produced readily on mill order. For example, the standard size for 1-in.-diam low-carbon bar is 1.000 to 0.998 in.

Low-Alloy Steels

Although alloy steels have somewhat better properties than carbon steels either as hot rolled or as cold drawn, the cost of alloy content is usually justified only when quenching and tempering develops the full potentialities.

The most important exceptions are the so-called "low-alloy" steels for structural components that require forming and welding characteristics similar to those of low-carbon structural steels but with improved mechanical properties. These low-alloy steels are used as rolled or as annealed, depending on the formability required. They are discussed fully on page 534 of the 1948 Handbook. To the compositions listed in that article should be added those containing up to 0.25% C and up to 1.60% Mn, which are now within the weldable range with present-day techniques, even though conditions for satisfactory weldability become more restricted as both carbon and manganese rise. Although available in many commercial forms, these steels are used principally as flat rolled products and structural shapes.

Table II. Size Variations of Cold Drawn Carbon Steel Bars

Size, in.	Carbon Content or Condition			
	Max 0.28% C or Less	Max 0.28 to 0.55% C	Stress Relieved Bars	Max Over 0.55% C
Undersize Variations, in.				
To 1 incl.	0.002	0.003	0.004	0.006
Over 1 to 2 incl.	0.003	0.004	0.006	0.008
Over 2 to 4 incl.	0.004	0.005	0.008	0.010
Over 4 to 6 incl.	0.005	0.006	0.010	0.012
Over 6 to 7½ incl.	0.006	0.008	0.012	0.016
Rounds, Cold Drawn or Turned and Polished				
To 1½ incl.	0.002	0.003	0.004	0.006
Over 1½ to 1 incl.	0.003	0.004	0.006	0.008
Over 1 to 2½ incl.	0.004	0.005	0.008	0.010
Over 2½ to 3½ incl.	0.005	0.006	0.010	0.012
Hexagons, Cold Drawn				
To 1½ incl.	0.002	0.003	0.004	0.006
Over 1½ to 1 incl.	0.003	0.004	0.006	0.008
Over 1 to 2½ incl.	0.004	0.005	0.008	0.010
Over 2½ to 3½ incl.	0.005	0.006	0.010	0.012
Squares, Cold Drawn				
Over 1½ incl.	0.003	0.004	0.006	0.008
Over 1½ to 1 incl.	0.004	0.005	0.008	0.010
Over 1 to 2½ incl.	0.005	0.006	0.010	0.012
Over 2½ to 4 incl.	0.006	0.008	0.012	0.016

But a part may require 0.995 to 0.993-in. diam. If the steel can be ordered in mill quantity, the exact size required can be produced, thus saving a grinding operation when the mill finish on the bar is satisfactory. A further advantage applying only to cold drawn bars is improved machinability, which is greatest in the low-carbon steels but is still appreciable at the higher carbon levels.

Good use of these high-strength, cold finished steels is illustrated by an actual example in the selection of stud material for a new engine. Originally, 8642-H, quenched and tempered to a minimum yield strength of 110,000 psi, was specified. In testing the engine, calculations and strain measurements showed that main bearing studs were correctly specified but the cylinder head studs were over-specified. The stress was low enough so that C-1141, cold drawn and stress relieved to 95,000 psi minimum yield strength, was entirely satisfactory. By this change, cost was reduced through the use of a cheaper steel of better machinability, and there was no sacrifice in the serviceability of the engine.

Hardenable Steels

When the strength or the combination of strength and notched-bar toughness required by the part cannot be met by steel as rolled, forged, normalized or cold drawn, quench hardening and tempering must be used to obtain the necessary properties. Both carbon and alloy steels respond to such treatment but in different degree. Carbon steel is always lower in first cost but may be higher in final cost because of processing considerations. Also, specific advantages peculiar to alloy steel may dictate its use. The following discussion will be based primarily on those applications in which some portion of the cross section is quenched to martensite or to bainite and then tempered as required.

Hardenability of steel is defined as that property which determines the depth and distribution of hardness induced by quenching. Since, in this type of treatment, the primary concern is to obtain a satisfactory reaction to the quench, it follows that, of all the factors affecting the selection of steel

Hot Rolled and Cold Finished Bars

Estimated Mechanical Properties of Carbon Steels

GRADE NO. AND PROCESSING	EXPECTED MINIMUM VALUES						GRADE NO. AND PROCESSING	EXPECTED MINIMUM VALUES					
	T.S.	Y.S.	ELONG.	R.A.	BRI- NELL	MACH- INING*		T.S.	Y.S.	ELONG.	R.A.	BRI- NELL	MACH- INING*
1006 Hot rolled 43,000 24,000 30 55 86							1050 Hot rolled 90,000 49,500 15 35 179						
Cold drawn 48,000 41,000 20 45 95 48							Cold drawn 100,000 84,000 10 30 197 51						
1008 Hot rolled 44,000 24,500 30 55 86							1052 Hot rolled 108,000 59,500 12 30 217						
Cold drawn 49,000 41,500 20 45 95 50							1055 Hot rolled 94,000 51,500 12 30 192						
1009 Hot rolled 43,000 24,000 30 55 86							1060 Hot rolled 98,000 54,000 12 30 201						
Cold drawn 48,000 41,000 20 45 95 48							1062 Hot rolled 103,000 56,500 12 30 212						
1010 Hot rolled 47,000 26,000 28 50 95							1064 Hot rolled 97,000 53,500 12 30 201						
Cold drawn 53,000 44,000 20 40 105 52							1065 Hot rolled 100,000 55,000 12 30 207						
1012 Hot rolled 48,000 26,500 28 50 95							1066 Hot rolled 106,000 58,000 12 30 217						
Cold drawn 54,000 45,000 19 40 105 52							1070 Hot rolled 102,000 56,000 12 30 212						
1015 Hot rolled 50,000 27,500 28 50 101							1074 Hot rolled 105,000 58,000 12 30 217						
Cold drawn 56,000 47,000 18 40 111 53							1078 Hot rolled 100,000 55,000 12 30 207						
1016 Hot rolled 55,000 30,000 25 50 111							1080 Hot rolled 112,000 61,500 10 25 229						
Cold drawn 61,000 51,000 18 40 121 64							1084 Hot rolled 119,000 65,500 10 25 241						
1017 Hot rolled 53,000 29,000 26 50 105							1085 Hot rolled 121,000 66,500 10 25 248						
Cold drawn 59,000 49,000 18 40 116 56							1086 Hot rolled 112,000 61,500 10 25 229						
1018 Hot rolled 58,000 32,000 25 50 116							1090 Hot rolled 122,000 67,000 10 25 248						
Cold drawn 64,000 54,000 15 40 126 66							1095 Hot rolled 120,000 66,000 10 25 248						
1019 Hot rolled 59,000 32,500 25 50 116													
Cold drawn 66,000 55,000 15 40 131 70													
1020 Hot rolled 55,000 30,000 25 50 111													
Cold drawn 61,000 51,000 15 40 121 58													
1022 Hot rolled 62,000 34,000 23 47 121													
Cold drawn 69,000 58,000 15 40 137 69													
1023 Hot rolled 56,000 31,000 25 50 111													
Cold drawn 62,000 52,500 15 40 121 58													
1024 Hot rolled 74,000 41,000 20 42 149													
Cold drawn 82,000 69,000 12 35 163 64													
1025 Hot rolled 58,000 32,000 25 50 116													
Cold drawn 64,000 54,000 15 40 126 58													
1027 Hot rolled 75,000 41,000 18 40 149													
Cold drawn 83,000 70,000 12 35 163 64													
1030 Hot rolled 68,000 37,500 20 42 137													
Cold drawn 76,000 64,000 12 35 149 68													
1033 Hot rolled 72,000 39,500 18 40 143													
Cold drawn 80,000 67,000 12 35 163 68													
1035 Hot rolled 72,000 39,500 18 40 143													
Cold drawn 80,000 67,000 12 35 163 65													
1036 Hot rolled 83,000 45,500 16 40 163													
Cold drawn 92,000 77,500 12 35 187 54													
1037 Hot rolled 74,000 40,500 18 40 143													
Cold drawn 82,000 69,000 12 35 167 65													
1038 Hot rolled 75,000 41,000 18 40 149													
Cold drawn 83,000 70,000 12 35 163 62													
1039 Hot rolled 79,000 43,500 16 40 156													
Cold drawn 88,000 74,000 12 35 179 61													
1040 Hot rolled 76,000 42,000 18 40 149													
Cold drawn 85,000 71,000 12 35 170 62													
1041 Hot rolled 92,000 51,000 15 40 187													
Cold drawn 102,500 87,000 10 30 207 50													
1042 Hot rolled 80,000 44,000 16 40 163													
Cold drawn 89,000 75,000 12 35 179 60													
1043 Hot rolled 82,000 45,000 16 40 163													
Cold drawn 91,000 77,000 12 35 179 58													
1045 Hot rolled 82,000 45,000 16 40 163													
Cold drawn 91,000 77,000 12 35 179 55													
1046 Hot rolled 85,000 47,000 15 40 170													
Cold drawn 94,000 79,000 12 35 187 54													
1049 Hot rolled 87,000 48,000 15 35 179													
Cold drawn 97,000 81,500 10 30 197 53													

* Machinability based on 100% for 1112, cold drawn.

From a report of S.A.E. Iron and Steel Technical Committee as revised January 1953. Figures are for information rather than specification purposes, and apply to bars ranging from $\frac{1}{4}$ to $1\frac{1}{4}$ in. in size as determined from standard 0.505-in. tension test pieces with 2-in. gage length. Smaller sizes will generally be somewhat stronger; larger sizes have somewhat lower values than those quoted.

Averages for cold drawn bars are for commercial production, wherein hot rolled rounds are given a single draft,

the reduction in diameter ($\frac{1}{4}$ to $\frac{1}{2}$ in.) being roughly proportional to size, but it also depends on shape and composition. A considerable variation from these averages can result from special mill practices by prearrangement with the supplier.

Physical values for turned, ground and polished bars correspond to averages quoted for hot rolled.

Consult "Steel Products Manual, Section 9, Cold Finished Carbon Steel Bars", by American Iron and Steel Institute.

for heat treated parts, hardenability is by far the most important single consideration. Hardenability should not be confused with hardness per se or with maximum hardness. The maximum hardness attainable with any steel is a function of carbon content (see Fig. 1, page 621, 1948 Handbook).

Hardenability is governed principally by chemical composition and grain size; certain other factors in the steel-making process also affect it. Hardenability is measured by the standard end-quench test discussed on page 489 of the 1948 Handbook. All alloy steels commonly used for machinery can be purchased on a hardenability basis, and developments in carbon steels are in that direction. To produce certain parts with exact requirements, some users now test carbon steels for hardenability and apply them accordingly.

The true measure of applicability of any steel to a part requiring heat

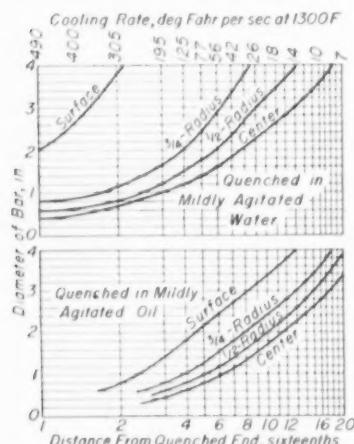


Fig. 3. Correlation of Identical Cooling Rates in End-Quenched Hardenability Specimen and Quenched Round Bars (SAE Handbook, 1953)

treatment is the relation of its hardenability to the critical cross section of the part at the time it is heat treated. By critical cross section is meant that section of the part where service stresses are highest and, therefore, where the highest mechanical properties are required. For example, if the part is a rough forging of $2\frac{1}{2}$ -in. diam at the critical cross section, which is later machined to 2-in. diam, and the finished part must be hardened to $\frac{1}{4}$ -inch-radius (that is, $\frac{1}{4}$ in. deep) then the hardenability of the steel must be such that the rough forging will harden $\frac{1}{2}$ in. deep. Figure 3 shows the correlation between cooling rates along the end-quench hardenability specimen and four locations in round bars up to 4-in. diam for both oil and water quenching. For flat bars of width equal to or greater than four times the thickness, the hardenability is 65 to 70% of that shown for round bars. In applying these data, both the quenching medium and the required depth of hardening for the part must be considered.

Quenching Medium. The amount of distortion that can be tolerated often determines the steel and quenching medium. Except in small sections, carbon steels nearly always require water

quenching and serve best in parts quenched in the rough condition where relatively large dimensional changes can usually be tolerated. When the steel is to be heat treated after machining, water quenching can cause serious distortion and breakage at shoulders, undercuts and keyways. Oil quenching is often the only practical answer, and this usually requires alloy content in the steel, to provide the hardenability demanded by the section.

The basic considerations in determining the quenching medium are:

- 1 For any given carbon level, carbon steels have lower hardenability than alloy steels.
- 2 Water has a higher quenching rate than oil, and agitation increases the rate of either (see "Agitation of Quenching Mediums", this volume).
- 3 The more severe the quench, the greater is the dimensional change (distortion) that results from the quench, except as it may be reduced by special techniques.
- 4 Because of this distortion and the danger of quench cracks, the quench should be no more severe than required by the hardenability of the steel.

Selected Depth of Hardening. The depth to which parts are hardened not only may affect the serviceability of the parts but it always affects the hardenability required and therefore the cost. A survey of automotive vehicles showed that hardening to 80% or more martensite at $\frac{1}{4}$ -radius of the part as finished was generally sufficient. In some parts, less depth is required; this is true even of some steering knuckles, which are subject to severe shock loads. Such parts are designed for low deflection under load, and even the surface layers are only moderately stressed.

On the other hand, parts loaded principally in tension, such as bolts, and parts operating at high hardness levels, such as springs of all types, must be hardened more nearly through the section. In the automobile leaf spring discussed earlier, the leaves are designed with a low section modulus in the direction of loading. The allowable deflection is large and most of the cross section is highly stressed.

The hardening need be no deeper than is required to provide the strength to sustain the load at any given depth below the surface. This rule takes advantage of the fact that, except for uni-axial tension or compression, the stress is highest at the surface and decreases linearly to zero at the neutral axis. The idea that all heat treated parts should be hardened completely throughout the cross section cannot be justified on the basis of either theory or practice.

Carbon Steels. To show the application of hardenability data, representative values for 1042 steel (Table III) may be considered in relation to Fig. 3. For the low limit of carbon for this steel, 0.40%, a commercially acceptable minimum hardness is Rockwell C 45, as quenched. This value occurs in the minimum column of Table III at $2\frac{1}{16}$ in. from the quenched end of the hardenability test specimen, which corresponds to a cooling rate of 305 F per sec at 1300 F. The intersection of the $2\frac{1}{16}$ vertical lines (upper half of Fig. 3) with the curve marked "Center", gives the largest size round of 1042 steel that can be water quenched to

produce Rockwell C 45 at the center, and is found to be $\frac{1}{4}$ in., reading on the left-hand vertical axis. Similarly, the largest size that can be water quenched to Rockwell C 45 at $\frac{3}{4}$ -radius is $1\frac{1}{4}$ in., which corresponds to a depth of hardening of approximately 0.140 in. By using a similar process on the lower part of Fig. 3, the largest size round of 1042 steel that can be hardened to Rockwell C 45 at the center in oil is found to be about 0.2-in. diam; and for $\frac{3}{4}$ -radius, about $\frac{1}{2}$ -in. diam.

In spite of these apparently serious limitations in the hardenability of this

Table III. Representative Hardenability Test Values for 1042 Steel

Distance from Quenched End, in.	Rockwell C Hardness Minimum	Rockwell C Hardness Maximum
1/16	53	61
2/16	45	58
3/16	30	52
4/16	27	38
5/16	26	30
6/16	24	29
7/16	23	28
8/16	22	27
10/16	21	26

and other carbon steels, they are, as a means of reducing steel cost, very frequently used successfully in much heavier sections than those just referred to, despite some irregularities in heat treating behavior and the development of less-than-optimum mechanical properties. The tempering temperature will be correspondingly lower and highly variable if normally accepted final hardness ranges are to be maintained. The tensile strength will, as always, be a function of the final hardness but the yield strength will be lower than normal and will show a wide and unpredictable variation. The shock resistance may be seriously impaired. In spite of these shortcomings, if the steel does not give so much processing trouble as to be uneconomical and if the results in service are satisfactory, the application is a success by commercial standards, because a part need be only just good enough for the intended life. There is no rule for determining in advance the success of such an application. Intimate knowledge of what has been successful in similar designs is the only guide.

Alloy Steels. The charts on pages 16 to 20-E show composition limits and hardenability bands for the current (1954) list of SAE-AISI alloy steels that can be purchased on a hardenability basis. Such steels are designated by the letter "H" following the composition code. The charts include all the commonly used alloy steels. The table on pages 8 and 9 summarizes the same hardenability data shown graphically for the H-steels on pages 16 to 20-E. Compositions are compiled on page 7.

The lists of standard steels change from year to year as new compositions are added on the basis of usage and existing ones removed for lack of it. For the listings of these H-steels and their hardenability limits, the latest SAE or AISI publications on this subject should be consulted.

When sizes larger than shown to be within the limits for carbon steel must be hardened, alloy steels must be used; the necessary hardenability can be ob-

Composition Limits of Standard H-Steels (February 1954)
 (Open hearth and electric furnace steel bars, billets and blooms not exceeding
 200-sq in. cross-sectional area, or 18-in. width or 10,000-lb weight per piece)

AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
1330-H	0.27 to 0.33	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1650	1600
1335-H	0.32 to 0.38	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1600	1550
1340-H	0.37 to 0.44	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1600	1550
2515-H	0.12 to 0.18	0.30 to 0.70	0.20 to 0.35	4.70 to 5.30	.....	.....	1700	1550
2517-H	0.14 to 0.20	0.30 to 0.70	0.20 to 0.35	4.70 to 5.30	.....	.....	1700	1550
3120-H	0.17 to 0.23	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1700	1700
3130-H	0.27 to 0.33	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1650	1600
3135-H	0.32 to 0.38	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1600	1550
3140-H	0.37 to 0.44	0.60 to 1.00	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1600	1550
3310-H	0.07 to 0.13	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	1.30 to 1.80	.....	1700	1550
3316-H	0.13 to 0.19	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	1.30 to 1.80	.....	1700	1550
4032-H	0.29 to 0.35	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1650	1600
4037-H	0.34 to 0.41	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4042-H	0.39 to 0.46	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4047-H	0.44 to 0.51	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4053-H	0.49 to 0.56	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4063-H	0.59 to 0.69	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4068-H	0.62 to 0.72	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4118-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.30 to 0.70	0.08 to 0.15	1700	1700
4130-H	0.27 to 0.33	0.30 to 0.70	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1650	1600
4135-H	0.32 to 0.38	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4137-H	0.34 to 0.41	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4140-H	0.37 to 0.44	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4142-H	0.39 to 0.46	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4145-H	0.42 to 0.49	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4147-H	0.44 to 0.51	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4150-H	0.47 to 0.54	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4320-H	0.17 to 0.23	0.40 to 0.70	0.20 to 0.35	1.55 to 2.00	0.35 to 0.65	0.20 to 0.30	1700	1700
4337-H	0.34 to 0.41	0.55 to 0.90	0.20 to 0.35	1.55 to 2.00	0.65 to 0.95	0.20 to 0.30	1600	1550
4340-H	0.37 to 0.44	0.55 to 0.90	0.20 to 0.35	1.55 to 2.00	0.65 to 0.95	0.20 to 0.30	1600	1550
4620-H	0.17 to 0.23	0.35 to 0.75	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1700	1700
X4620-H	0.17 to 0.23	0.40 to 0.80	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1700	1700
4621-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1700	1700
4640-H	0.37 to 0.44	0.50 to 0.90	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1650	1600
4812-H	0.09 to 0.15	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1700
4815-H	0.12 to 0.18	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
4817-H	0.14 to 0.20	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
4820-H	0.17 to 0.23	0.40 to 0.80	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
5120-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1700	1700
5130-H	0.27 to 0.33	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	.....	1650	1600
5132-H	0.29 to 0.35	0.50 to 0.90	0.20 to 0.35	.....	0.65 to 1.10	.....	1650	1600
5135-H	0.32 to 0.38	0.50 to 0.90	0.20 to 0.35	.....	0.70 to 1.15	.....	1650	1550
5140-H	0.37 to 0.44	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5145-H	0.42 to 0.49	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5147-H	0.45 to 0.52	0.60 to 1.05	0.20 to 0.35	.....	0.80 to 1.25	.....	1600	1550
5150-H	0.47 to 0.54	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5152-H	0.48 to 0.55	0.60 to 1.00	0.20 to 0.35	.....	0.85 to 1.30	.....	1600	1550
5160-H	0.55 to 0.65	0.65 to 1.10	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
6120-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	0.10 min	1700	1700
6145-H	0.42 to 0.49	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 min	1650	1600
6150-H	0.47 to 0.54	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 min	1650	1600
8617-H	0.14 to 0.20	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1700	1700
8620-H	0.17 to 0.23	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1700	1700
8622-H	0.19 to 0.25	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.13 to 0.25	1700	1700
8625-H	0.22 to 0.28	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1650	1600
8627-H	0.24 to 0.30	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1650	1600
8630-H	0.27 to 0.33	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1650	1600
8635-H	0.32 to 0.36	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8637-H	0.34 to 0.41	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8640-H	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8641-H ^(a)	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8642-H	0.39 to 0.46	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8645-H	0.42 to 0.49	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8650-H	0.47 to 0.54	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8653-H	0.49 to 0.56	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.50 to 0.85	0.15 to 0.25	1600	1550
8655-H	0.50 to 0.60	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8660-H	0.55 to 0.65	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8720-H	0.17 to 0.23	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1700	1700
8740-H	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
8742-H	0.39 to 0.46	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
8750-H	0.47 to 0.54	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
9260-H	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	0.05 to 0.35	.....	1650	1600
9261-H	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	0.20 to 0.50	.....	1650	1600
9262-H	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	0.20 to 0.50	.....	1650	1600
9310-H	0.07 to 0.13	0.40 to 0.70	0.20 to 0.35	2.95 to 3.55	1.00 to 1.45	0.08 to 0.15	1700	1550
9840-H	0.37 to 0.44	0.60 to 0.95	0.20 to 0.35	0.80 to 1.20	0.65 to 0.95	0.20 to 0.30	1600	1550
9850-H	0.47 to 0.54	0.60 to 0.95	0.20 to 0.35	0.80 to 1.20	0.65 to 0.95	0.20 to 0.30	1600	1550
86B45-H ^(b)	0.42 to 0.49	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550

(a) Sulfur content 0.040 to 0.060%. (b) This grade can be expected to have 0.0005% min boron.
 The phosphorus and sulfur limitations for each steelmaking process are as follows: basic electric furnace, 0.025% max; basic open hearth, 0.040% max; acid electric furnace, 0.050% max; acid open hearth, 0.050% max. The minimum silicon limit for acid

open hearth or acid electric furnace alloy steel is 0.15%. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present in the following maximum amounts: Cu, 0.35%; Ni, 0.25%; Cr, 0.20%; and Mo, 0.06%. Heat treating temperatures as recommended by SAE

Hardness Limits of H-Steels for Specification Purposes (Standard End-Quench Hardenability Test)

(For hardenability bands, see page 16 and following; for chemical compositions, see page 7.)

Distance
from
Quenched
End, Six-
teenths
of an in.

AISI-SAE H-Steels: Data as of February 1954

	Rockwell C Hardness												Rockwell C Hardness											
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
	1330-H	1335-H	1340-H	2515-H	2517-H	3120-H	3130-H	3135-H	3140-H	3310-H														
1	56	49	58	51	60	53	45	38	46	39	48	41	56	49	58	51	60	53	43	46	40			
2	56	47	57	49	60	52	44	37	46	38	47	39	55	47	57	50	60	52	43	46	40			
3	55	44	56	47	59	51	43	33	46	35	44	34	54	44	56	49	59	50	43	35				
4	53	40	55	44	58	49	42	30	45	31	42	30	52	42	55	47	59	49	42	35				
5	52	35	54	38	57	46	41	27	44	28	38	25	51	38	54	44	58	47	42	34				
6	50	31	52	34	56	40	49	24	43	25	35	23	49	34	53	41	57	45	42	33				
7	48	28	50	31	55	35	38	22	42	23	32	21	48	32	51	37	57	43	41	32				
8	45	26	48	29	54	33	37	20	41	21	30	20	45	30	50	35	56	41	41	31				
9	43	25	46	27	52	31	35	..	39	20	29	..	43	29	48	33	55	38	41	30				
10	42	23	44	26	51	29	34	..	37	..	28	..	41	28	46	31	54	36	40	30				
11	40	22	42	25	50	28	32	..	35	..	27	..	39	26	44	30	53	34	40	29				
12	39	21	41	24	48	27	31	..	34	..	27	..	38	25	42	29	52	33	40	29				
13	38	20	40	23	46	26	30	..	33	..	26	..	36	24	40	29	51	32	39	28				
14	37	..	39	22	44	25	29	..	32	..	26	..	35	24	39	28	50	31	39	28				
15	36	..	38	22	42	25	29	..	32	..	25	..	34	23	35	27	49	30	38	27				
16	35	..	37	21	41	24	28	..	31	..	25	..	34	22	37	26	48	30	38	27				
17	34	..	35	20	39	23	27	..	30	..	24	..	33	21	36	25	46	29	37	26				
18	33	..	34	..	38	23	26	..	29	..	23	..	32	20	35	23	44	28	37	26				
19	32	..	33	..	37	22	25	..	28	..	23	..	32	21	34	22	43	28	37	26				
20	31	..	32	..	36	22	24	..	27	..	22	..	31	21	34	20	42	27	36	26				
21	31	..	31	..	35	21	24	..	27	..	22	..	31	21	34	20	41	27	36	25				
22	30	..	31	..	35	21	23	..	26	..	21	..	31	21	34	20	40	26	36	25				
23	30	..	30	..	34	20	23	..	26	..	21	..	30	20	33	23	39	26	35	25				
24	29	..	30	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
25	28	..	29	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
26	27	..	28	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
27	26	..	27	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
28	25	..	26	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
29	24	..	25	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
30	23	..	24	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
31	22	..	23	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
32	21	..	22	..	34	20	22	..	25	..	21	..	30	20	33	23	38	26	35	25				
	3316-H	4032-H	4037-H	4042-H	4047-H	4053-H	4063-H	4068-H	4118-H	4120-H														
1	47	40	57	50	59	52	62	55	64	57	65	59	..	60	..	60	48	41	56	49				
2	47	39	54	45	57	49	60	52	62	55	65	59	..	60	..	60	46	36	55	46				
3	47	38	51	36	54	42	58	48	60	50	64	57	65	58	..	60	41	27	53	42				
4	46	38	46	29	51	35	53	40	58	42	62	53	65	56	..	59	35	23	51	38				
5	46	37	39	25	45	30	50	33	55	35	61	45	65	50	..	51	20	49	34					
6	45	36	34	23	38	26	45	29	52	32	59	38	64	45	..	45	28	..	47	31				
7	45	36	31	22	34	23	39	27	47	30	57	34	62	36	63	39	27	..	44	29				
8	45	35	29	21	32	22	36	26	43	28	55	32	61	35	62	36	25	..	42	27				
9	45	34	28	20	30	21	34	25	40	28	51	31	59	34	60	35	24	..	40	26				
10	45	33	26	..	29	20	33	24	38	27	47	30	57	33	58	34	23	..	38	26				
11	45	33	26	..	28	..	32	24	37	26	44	29	54	32	55	33	22	..	36	25				
12	45	32	25	..	27	..	31	23	35	26	42	29	51	32	52	33	21	..	35	25				
13	45	32	24	..	26	..	30	23	34	25	40	28	53	32	52	33	21	..	34	24				
14	44	32	24	..	26	..	30	23	34	25	38	28	46	31	45	32	20	..	33	23				
15	44	31	23	..	25	..	29	22	32	25	36	28	43	31	44	32	20	..	33	23				
16	44	31	23	..	25	..	29	22	31	24	34	27	40	31	41	30	20	..	32	22				
17	44	31	23	..	25	..	29	22	31	24	34	27	40	31	41	30	20	..	32	22				
18	43	30	49	33	53	35	56	37	58	39	59	41	60	49	61	50	39	41	24	..	55	41	57	45
19	40	27	43	30	48	32	53	34	55	36	57	38	59	40	60	49	39	40	24	..	55	40	57	44
20	39	27	42	30	47	32	52	34	55	35	57	37	58	39	60	49	39	40	24	..	55	39	57	43
21	38	26	42	29	46	31	51	34	55	35	57	37	58	38	60	49	39	40	24	..	54	39	56	42
22	38	26	41	29	45	31	51	33	55	34	56	37	58	38	60	49	39	40	24	..	54	39	56	41
23	38	26	41	29	45	31	51	33	55	34	56	37	58	38	60	49	39	40	24	..	54	39	56	41
24	37	26	41	29	44	30	50	33	54	35	56	37	58	38	60	49	39	40	24	..	53	39	56	41
25	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
26	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
27	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
28	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
29	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
30	37	26	41	29	44	30	50	33	54	35	56	36	58	38	60	49	39	40	24	..	53	39	56	41
31	37	26	41	29	44	30	50	33	54	35	56	36	58</											

Hardness Limits of H-Steels (Continued)

(For hardenability bands, see page 20-A and following; for chemical compositions, see page 7.)

Distance from Quenched End, Six- teenths of an in.	AISI-SAE H-Steels; Data as of February 1954																		6120-II					
	5130-II			5132-II			5135-II			5140-II			5145-II			5147-II			5150-II			5152-II		
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	56	49	57	50	58	51	60	53	63	56	64	57	65	59	65	59	65	59	..	60	48	40		
2	55	46	56	47	57	49	59	52	62	55	64	56	65	58	65	58	65	58	..	60	47	38		
3	53	42	54	43	56	47	58	50	61	53	63	55	64	57	65	58	65	58	..	60	45	33		
4	51	39	52	40	55	43	57	48	60	51	62	54	63	56	64	57	65	59	42	29				
5	49	35	50	35	51	36	56	43	59	48	62	53	62	53	63	56	65	58	39	26				
6	47	32	48	32	52	35	54	38	58	42	61	52	61	49	63	55	64	56	36	24				
7	45	30	45	29	50	32	52	35	57	38	61	49	60	42	62	53	64	52	34	23				
8	42	28	42	27	47	30	50	33	56	35	60	45	59	38	62	51	63	47	33	22				
9	40	26	40	25	45	28	48	31	55	33	60	40	58	36	61	48	62	42	32	21				
10	38	25	38	24	43	27	46	30	53	32	59	37	56	34	60	45	61	39	31	21				
11	37	23	37	23	41	25	45	29	52	31	59	35	55	33	60	42	60	37	31	20				
12	36	22	36	22	40	24	43	28	50	30	58	34	53	32	59	39	59	36	31	20				
13	35	21	35	21	39	23	42	27	48	30	58	33	51	31	59	38	58	35	30	20				
14	34	20	34	20	38	22	40	27	47	29	57	32	50	31	58	37	56	35	30	20				
15	34	..	34	..	37	21	39	26	45	28	57	32	48	30	58	36	54	34	29	..				
16	33	..	33	..	37	21	38	25	44	28	56	31	47	30	57	35	52	34	29	..				
17	32	..	32	..	36	20	37	24	42	26	55	30	45	29	56	34	48	33	28	..				
18	31	..	31	..	35	..	36	23	41	25	54	29	43	28	55	32	47	32	28	..				
19	30	..	30	..	34	..	35	21	39	24	53	27	42	27	53	31	46	31	27	..				
20	29	..	29	..	33	..	34	20	38	23	52	26	41	26	51	30	45	30	26	..				
21	27	..	28	..	32	..	34	..	37	22	51	25	40	25	50	29	44	29	25	..				
22	26	..	27	..	32	..	33	..	37	21	50	24	39	24	48	27	43	28	25	..				
23	25	..	26	..	31	..	33	..	36	..	49	22	39	23	47	26	43	28	24	..				
24	24	..	25	..	30	..	32	..	35	..	48	21	38	22	45	25	42	27	23	..				
25	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
26	6145-II	6150-II	8617-II	8620-II	8622-II	8625-II	8627-II	8630-II	8635-II	8637-II	..	..	..	..	..	..	..	..	..	..	..	..
1	63	56	65	59	46	39	49	41	50	43	52	45	54	47	56	49	58	51	59	52	..	..
2	63	55	65	56	44	33	47	37	49	39	51	41	52	43	55	46	57	49	58	51	..	..
3	62	54	64	57	41	27	44	32	47	34	48	36	50	36	54	43	56	47	58	50	..	..
4	62	54	64	56	38	24	41	27	44	30	46	32	48	35	52	39	55	45	57	48	..	..
5	61	52	63	55	34	20	37	23	40	26	43	29	45	32	50	35	54	42	56	45	..	..
6	61	49	63	53	31	..	34	21	37	24	40	27	43	29	47	32	53	39	55	42	..	..
7	60	45	62	50	28	..	32	..	34	22	37	25	40	27	44	29	51	35	54	39	..	..
8	59	42	61	47	27	..	30	..	32	20	35	23	38	26	41	28	50	33	53	36	..	..
9	58	39	61	43	26	..	29	..	31	..	33	22	36	24	39	27	48	31	51	34	..	..
10	57	38	60	41	25	..	28	..	30	..	32	21	34	24	37	26	46	30	49	32	..	..
11	56	37	59	39	24	..	27	..	29	..	31	20	33	23	35	25	45	29	47	31	..	..
12	55	36	58	36	23	..	26	..	28	..	30	..	32	22	34	24	43	28	46	30	..	..
13	54	35	57	37	23	..	25	..	27	..	29	..	31	21	33	23	41	27	44	29	..	..
14	52	35	55	36	22	..	25	..	26	..	28	..	30	21	33	22	40	26	43	28	..	..
15	51	34	54	35	22	..	24	..	26	..	28	..	30	20	32	22	38	25	41	27	..	..
16	50	33	52	35	21	..	24	..	25	..	27	..	29	20	31	21	37	25	40	26	..	..
17	49	32	50	34	21	..	23	..	25	..	27	..	28	..	30	21	36	24	39	25	..	..
18	48	31	48	32	20	..	23	..	24	..	26	..	28	..	30	20	35	23	37	25	..	..
19	47	30	47	31	20	..	23	..	24	..	26	..	28	..	29	20	34	23	36	24	..	..
20	46	29	46	30	20	..	23	..	24	..	26	..	27	..	29	20	33	23	35	24	..	..
21	45	27	45	29	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
22	44	26	44	27	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
23	44	25	42	28	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
24	43	25	42	27	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
25	42	24	41	25	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
26	41	24	40	25	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
27	40	23	40	24	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
28	39	22	40	23	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
29	38	21	40	22	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
30	37	20	39	21	20	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
31	37	24	39	26	21	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
32	37	24	39	26	21	..	22	..	24	..	26	..	27	..	29	20	33	22	35	24	..	..
33	36	29	36	30	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
34	35	28	35	29	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
35	34	28	34	30	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
36	33	27	33	29	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
37	32	27	32	29	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
38	31	26	31	28	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
39	30	25	30	27	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
40	29	24	29	26	21	..	32	..	34	..	36	..	38	..	40	..	42	..	44	..	46	..		
41	28																							

tained in no other way. For example, consider the hardenability of 8640-H. The commercially accepted limit for minimum reaction to a quench is 80% martensite. Figure 4 shows that for the minimum carbon content of this grade (0.37%) an 80% martensite structure has a hardness of Rockwell C 45. The hardenability band for 8640-H (page 20-C) gives the minimum end-quench distance at Rockwell C 45 as 6/16. From Fig. 3 it is noted the largest size round, corresponding to 6/16, that will harden to the center when oil quenched is 1 in. and for $\frac{1}{4}$ -radius, 1 $\frac{1}{2}$ in. No carbon steel will harden to these depths when oil quenched. (Water quenching is not considered because 8640-H is not usually so quenched in these sizes.)

When the service requirements are such that hardening must produce a higher percentage of martensite than the 80% usually accepted in commercial practice, the size that can be hardened to a given depth decreases rapidly.

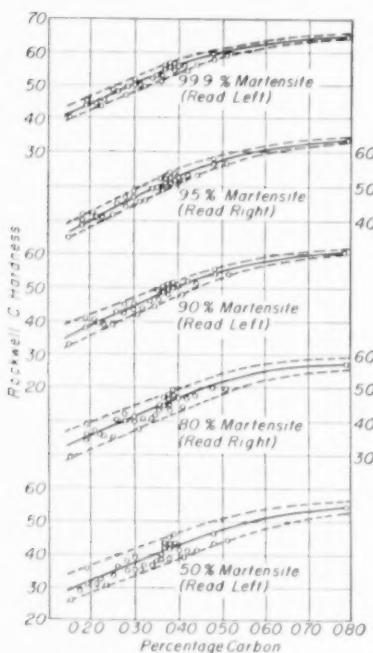


Fig. 4. Hardness of Martensite Structures as a Function of Carbon Content [Hodge and Orehoski, Trans AIME, 167, 627 (1946)]

Thus, for 8640-H on a 95% martensite basis, the minimum hardness would be Rockwell C 51 (Fig. 4). The largest size that can be hardened in oil would be $\frac{1}{4}$ in. to the center and 1 in. to $\frac{1}{4}$ -radius. Even the deepest-hardening of the commonly used alloy steels, 4340-H, will harden to the center in only a 2-in. size on a 95% martensite basis, whereas on an 80% basis (Rockwell C 45) a 3 $\frac{1}{2}$ -in. round will harden to the center in oil.

These examples illustrate the need for caution in deciding that very deep hardening or unusually high percentages of martensite in the hardened portion are necessary. The commonest result of such decisions is over-specification of steel and higher cost.

Selection Procedure

For quick reference in selection, Table IV lists in order of increasing cost (as of May 1954) steels that have the minimum hardenability necessary to meet the requirements of Rockwell C 45 at $\frac{1}{4}$ -radius, $\frac{1}{2}$ -radius and the center, for the maximum sections shown in the various columns. Selection should be based on Rockwell C 45 at $\frac{1}{4}$ -radius except where it is established that greater depth of hardening is required.

The size ranges given as column headings in each of the six parts of Table IV are necessarily arbitrary and they will not fit all problems. For example, if it is desired to know the lowest cost steel that will harden to $\frac{1}{4}$ -radius in $1\frac{1}{4}$ -in. cross section, the end-quench test bar distance should be found in Fig. 3 (7/16 for oil quench) and the hardenability bands on pages 16 to 20-E examined for a suitable steel.

As a simplification, Table IV is based on constant hardness (Rockwell C 45) as representing 80% martensite at all carbon levels. Figure 4 shows that this is not strictly true. Therefore, as previously explained, the most precise

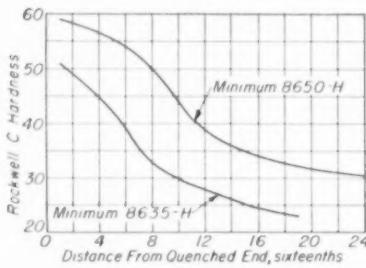


Fig. 5. Minimum Hardenability of 8635-H and 8650-H

selection of steel can be made by first finding the hardness level for the desired percentage of martensite at any carbon content from Fig. 4; then finding the end-quench distance for the required depth of hardening from Fig. 3 and, finally, selecting a steel having the desired minimum hardness at the proper end-quench distance, from the hardenability bands. Table IV is accurate enough for many commercial purposes.

Heat Treating Conditions. The conditions of heat treatment to produce the anticipated results are:

- 1 The furnace should have a suitable protective atmosphere.
- 2 Pieces should be loaded in the furnace so that each part is adequately heated to hardening temperature.
- 3 Pieces should be quenched so as to allow good access of quenching fluid to each part.
- 4 Agitation of the oil or water should be provided or the piece should be kept moving in the quench.
- 5 The quenching oil should be maintained between 90 and 140 F. Quenching water should be kept below 80 F.

Effect of Carbon. So far, the minimum hardenability required of a steel has been considered in relation to the critical cross section of the part, and it has been established that if excess hardenability is supplied, one result will be increased cost of steel. This is one factor in determining the upper

limit of applicable hardenability. The other principal limiting factor is the hardenability imparted by carbon. Figure 5 shows the difference between the minimum hardenability curves for 8635-H and 8650-H, wherein the alloy content is approximately the same and the effects of carbon alone can be clearly seen. The hardness effect is shown by the vertical distance between the two curves at the 1/16 position—that is, a difference of 8 points Rockwell C. The hardenability effect is read on the horizontal axis. Taking Rockwell C 45 as an example, this effect is 6/16 (10/16 minus 4/16).

It must be clearly understood that the illustrated hardenability effect of carbon is for this particular steel only; it will be different for other steels. Furthermore, the effect of carbon alone is very much less than when it is in combination with an alloying element. Actually, the hardenability effects of carbon and the alloying elements, including manganese, when used in combination are multiplicative, as discussed on page 494 of the 1948 Handbook.

Maximum Hardenability for Minimum Section. Practical advantage is often taken of this hardenability effect of carbon. For example, if it is found that 4137-H will not provide the necessary minimum hardenability, 4142-H might be tried. The minimum hardenability will be increased by 4/16 at Rockwell C 45, a worthwhile increase. The danger is that, by increasing carbon to provide greater hardenability, the maximum as-quenched hardness is also increased. Many parts have a thin section sensitive to both maximum hardenability and high as-quenched hardness, and because of this combined effect of higher carbon, such sections often break during quenching.

Consider for example a shaft of 2 $\frac{3}{4}$ in. diam with a flange $\frac{1}{2}$ in. thick upset on one end; bolt holes in the flange leave only $\frac{1}{8}$ in. of metal between the edge of the flange and hole. The maximum hardenability of 4137-H is not too high for these $\frac{1}{2}$ by $\frac{1}{8}$ -in. sections but Fig. 3 and 4 show that at Rockwell C 45 for 80% martensite, the minimum hardenability of 4137-H will not allow the shaft to be hardened to $\frac{1}{4}$ -radius. The hardenability of 4142-H is satisfactory for the shaft but the flange cracks at the bolt holes. The possible remedies are: (1) Drill the bolt holes after quenching and tempering; (2) reduce the effectiveness of the quench at the outer edge of the flange; (3) reduce the carbon content to that originally used but increase the alloy content enough to meet the hardenability requirements of the shaft.

In this example, the only steels that would meet the requirements with an oil quench would be 4337-H or 9840-H. Because of the thin flange section, water quenching of any steel except perhaps plain carbon would be certain to cause breakage and the shaft hardenability requirements cannot be met with plain carbon steel. Because of the cost of either of the oil-quenching alloy steels it would be well to try the first two suggested remedies.

There is need for even more caution in selecting carbon steels, especially for water quenching. These steels cannot be purchased on a hardenability basis (as of May 1954), and generally accepted quantitative information is lack-

ing. Therefore, reliance must be placed on experience, which has amply demonstrated that the carbon steels are not only sensitive to the minimum hardenability required by maximum section as shown by Table IV but, conversely, they are most sensitive to maximum hardenability at minimum section.

For example, consider a $\frac{3}{8}$ -in. diam shaft with a reduced section $\frac{3}{8}$ -in. diam, 1 in. long at one end, to be

quenched and tempered to Rockwell C 30 to 36. Because of the final hardness required, it is desirable to do all turning before hardening, and for good machining a free-cutting steel is needed. Close dimensional control is not a prime requirement. There is some cold drawn C-1137 in stock, and Table IV shows that this steel can be used if water quenched. When heat treated, the small end cracks. The

obvious remedy is to use C-1144, oil quenched (Table IV). The vital consideration is that the maximum hardenability permitted by the minimum section is often as important as the minimum hardenability required by the maximum section.

When the requirements of the minimum section govern selection, as shown by the above examples of alloy steel and carbon steel shafts, both the steel

Table IV. Selection of Uncarburized ("Through-Hardening") Steels by Hardenability Criteria

Steels of minimum hardenability necessary to meet the requirements of Rockwell C 45 at $\frac{3}{4}$ -radius, $\frac{1}{2}$ -radius and the center, as quenched, for the maximum sections shown in the various columns. Steels are listed in the order of increasing cost, as of May 1954.

Diameter of Piece as Quenched, in.						Diameter of Piece as Quenched, in.					
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3	Through	Over $\frac{3}{4}$	Over $1\frac{1}{2}$	Over 2	Over 3	Through
$\frac{1}{2}$	1	$1\frac{1}{2}$	2	3	4	$\frac{3}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$	2	3	4
Equivalent Position on End-Quench Hardenability Specimen						Equivalent Position on End-Quench Hardenability Specimen					
2 16	4 16	6 16	8 16	13 16	18 16	1 16	2 16	3 16	4 16	6 16	8 16

$\frac{3}{4}$ -Radius

Oil Quench

Selected to Develop Rockwell C 45 at $\frac{3}{4}$ -Radius as Quenched					
Water Quench					
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
$\frac{1}{2}$	1	$1\frac{1}{2}$	2	3	4

Diameter of Piece as Quenched, in.						Diameter of Piece as Quenched, in.					
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3	Through	Over $\frac{3}{4}$	Over $1\frac{1}{2}$	Over 2	Over 3	Through
$\frac{1}{2}$	1	$1\frac{1}{2}$	2	3	4	$\frac{3}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$	2	3	4
Equivalent Position on End-Quench Hardenability Specimen						Equivalent Position on End-Quench Hardenability Specimen					
3 16	5 16	7 1/2 16	10 16	15 16	20 16	1 16	3 16	4 16	6 16	9 16	12 16

$\frac{1}{2}$ -Radius

Oil Quench

Selected to Develop Rockwell C 45 at $\frac{1}{2}$ -Radius as Quenched					
Water Quench					
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
Through	Over $\frac{1}{2}$	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
$\frac{1}{2}$	1	$1\frac{1}{2}$	2	3	4

Diameter of Piece as Quenched, in.						Diameter of Piece as Quenched, in.					
Through	Over 0.4	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3	Through	Over 0.4	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
0.4	1	$1\frac{1}{2}$	2	3	4	0.4	1	$1\frac{1}{2}$	2	3	4
Equivalent Position on End-Quench Hardenability Specimen						Equivalent Position on End-Quench Hardenability Specimen					
3 16	6 16	8 1/2 16	12 16	17 1/2 16	26 16	1 16	3 16	5 1/2 16	8 16	13 16	18 16

Center

Oil Quench

Selected to Develop Rockwell C 45 at the Center as Quenched					
Water Quench					
Through	Over 0.4	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
Through	Over 0.4	Over 1	Over $1\frac{1}{2}$	Over 2	Over 3
$\frac{1}{2}$	1	$1\frac{1}{2}$	2	3	4

The steels shown in this table are those with **minimum** hardenability sufficient to develop a hardness of Rockwell C 45 at $\frac{3}{4}$ -radius, $\frac{1}{2}$ -radius or the center of sections of the **maximum** size shown in each column. This hardenability can be achieved with certainty only when the exterior surface of the part is machined prior to hardening and when the steel is heated in a protective atmosphere. Otherwise, it may be necessary to select a steel from the next column to the right to achieve the desired results.

At their **maximum** hardenability, all steels will meet the requirements for larger sizes. For example, at its minimum hardenability, 8640-H meets the 6 16 requirement; at its maximum hardenability, it meets more than the 13 16 requirement.

In making substitutions, any steel may be shifted to the left, that is, to a smaller section size, but caution is necessary in applying higher-carbon steels to lighter sections. For example, it is not recommended that 5160-H, oil quenched, be applied when the min-

imum hardenability requirement is 4 16.

When more than one carbon level in the same type of steel is shown in a column (for example, 1335-H and 1340-H) the steel with the higher carbon range will have the higher hardenability but its minimum hardenability is not sufficient to place it in the next column to the right.

Because of danger of quench cracking, all steels of 0.50% C or more, regardless of hardenability, have been eliminated from the tables for water quenching, except 5147-H (0.52% C max) in the last column under the $\frac{3}{4}$ -radius criterion.

Because of variation in chromium content, the 51xx-H steels in any column are listed in the order of increasing carbon content but not necessarily in the order of increasing cost.

*Hardenability is somewhat higher than the minimum required.

†Because of their higher carbon contents, these steels are more likely to crack during quenching.

selection and processing conditions become much more restricted than when the maximum section only must be considered. This is true for all steels in all size classifications listed in Table IV but, as stated previously, it is of particular importance in selecting carbon steels. It also explains why, regardless of hardenability, all steels of maximum 0.50% C and over, regardless of hardenability (except 5147-H), have been eliminated from those parts of Table IV which relate to water quenching. It may not be inferred that higher-carbon alloy steels will not crack in quenching. This is an ever-present danger when using deep-hardenning steels in any section and it is of particular concern in sections 3-in. diam and larger, even when they do not harden to the center.

Selection of Carbon Content. The significance of the relation between the hardness of as-quenched steel (Fig. 4) and the carbon content now becomes apparent. First, the higher-carbon steels transform to martensite at a lower temperature. At this temperature, the steel is less plastic and therefore less able to withstand the strains set up by the volume increase (about 1½%) when austenite transforms to martensite. Second, the higher-carbon martensites are harder and more brittle, and cannot withstand so well the severe strains set up in quenching; thus, pieces with unfavorable configuration, such as

stood that the relationship discussed here is for as-quenched martensite. It is a processing consideration only and does not apply to tempered martensite, the condition in which steels are used in service.

The foregoing discussion develops the reason for the closely spaced and

processing make use of the intermediate ranges.

The foregoing discussion may be summarized by saying that the most important function of the alloying elements in heat treatable steel is to increase hardenability. This effect makes possible, first, the hardening of larger sections than is possible with carbon steel, and, second, the use of the gentler oil quench to reduce distortion and sometimes to prevent breakage, thus improving quality and lowering the cost of manufacture. For a detailed discussion of the mechanism by which alloying elements produce these results, reference should be made to the article beginning on page 453 of the 1948 Handbook.

Similarity of Tensile Properties

When quenched to martensite and tempered to the same hardness, all carbon and alloy steels have similar tensile properties in that part of the cross section which reacts to the quench. If carbon steel has the hardenability required by the critical section of the part and the quench used, the resulting tensile strength, yield strength and percentage elongation in the fully hardened zone will be within the same range as the properties exhibited by a similar zone in an alloy steel quenched and tempered to the same hardness. This similarity in properties of the hardened zone holds regardless of the depth of hardening but, of course, the strength of the piece will be governed by the thickness of the hardened zone (depth of hardening).

Figure 6 shows the relation between hardness and tensile strength for all the commonly used constructional steels, both carbon and alloy, as quenched and tempered or as hot rolled. However, the relation is unreliable for cold drawn steels. Figure 7 shows the relation between yield

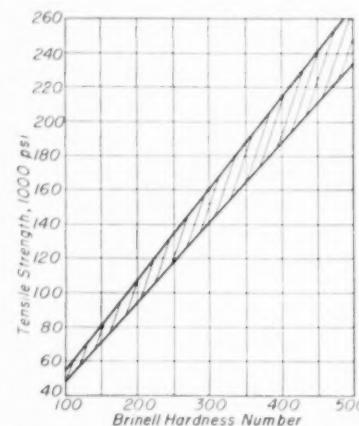


Fig. 6. Relation of Tensile Strength and Hardness for Hardened, As-Rolled, Annealed, and Normalized Steels (SAE Handbook, 1953)

overlapping carbon ranges for both carbon steels and alloy steels. At first glance, it appears that so many carbon ranges are unnecessary and that the number of available steels could be reduced. From the standpoint of engineering use alone this is true, but from a processing standpoint, there is demonstrated need for the steels listed. The innumerable combinations result-

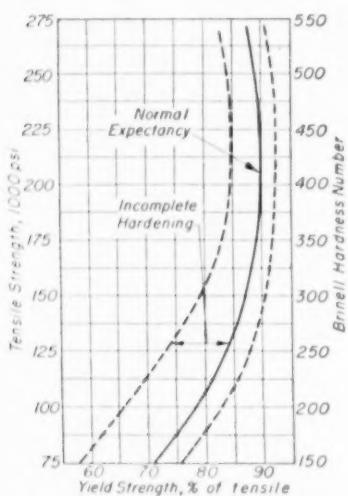


Fig. 7. Relation of Tensile Strength and Yield Strength for Quenched and Tempered Steels (SAE Handbook, 1953)

the shaft with flange, develop quench cracks. This brittle behavior of as-quenched martensite is sometimes encountered when uniform sections are hardened to the center, and it is an ever-present problem when large sections are hardened, especially if surface imperfections such as deep seams, notches and similar stress raisers are present.

An old rule for the selection of steels for heat treating states that the carbon content should be no higher than that necessary to produce the required hardness in quenching. The hardenability concept does not substantially alter this rule. It should be clearly under-

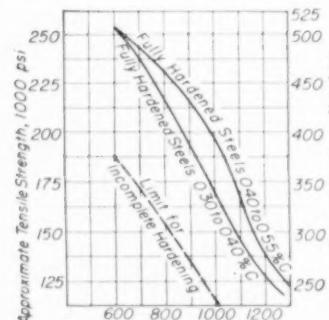


Fig. 8. Effect of Tempering Temperature on the Tensile Strength and Hardness of Carbon and Alloy Steels. Data from steels of 0.30 to 0.50% C (SAE Handbook, 1953)

ing from engineering requirements for mechanical properties, critical section of part with respect to both low and high hardenability, and the differences among various heating and quenching equipments, require fine gradations in steel composition to make mass production possible. The initial selection of steel for a part may well be in increments of 0.05% C—that is, 1035-1040-1045-etc. The later refinements to meet the often narrow limits between satisfactory and unsatisfactory

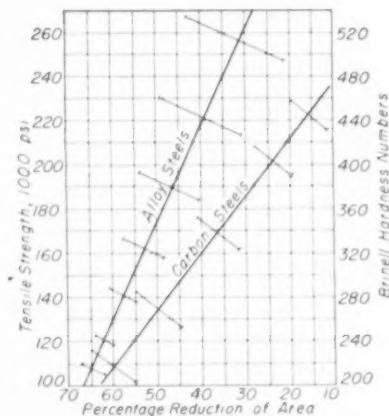


Fig. 9. Relation of Tensile Strength and Reduction of Area for Quenched and Tempered Steels (SAE Handbook, 1953)

strength and tensile strength: Fig. 8, the approximate hardness after tempering at different temperatures. The important exception is the relation between tensile strength and reduction of area; Fig. 9 shows that, for any tensile strength, the reduction of area of carbon steel is less than that of alloy

steel. In applications where this property is important, this difference must be taken into consideration but it should be noted, first, that the values do not drop to questionable levels until very high strength is reached and, second, that in many applications (for example, springs) low values of ductility do not impair service. In fact, within the limits of the section-hardenability relationship, more springs are made from carbon steel than from alloy steel. Thus it may be concluded that, in spite of some difference in resulting properties, the principal physical difference between carbon and alloy steels is hardenability.

When only the alloy steels are considered, it is found that, for all practical purposes, all compositions develop the same tensile properties when quenched to martensite and tempered to the same hardness. Figure 10 shows the range of properties for all commonly used alloy steels. It is evident that, except for the circumstances discussed below, alloy steels of the through-hardening grades can be se-

200 alloy steels are superior. This difference seems to be the result of two factors: First, with an equally effective quench for each steel, the alloy steel will have been tempered at a higher temperature. Second, the carbon steel, because of its lower hardenability, may have been less effectively quenched. This results in less uniform structure and makes necessary a further lowering of the tempering temperature, both of which contribute to decreased machinability.

In this connection, it will be noted from the hardenability data on pages 16 to 20-E that several alloy steels can be selected having substantially the same hardenability. Such a grouping can be narrowed by comparing the hardenability at constant carbon range, thus bringing into sharper focus the differences in hardenability between types of alloy steel. When there is no background of experience in the differences that may show up during processing because of the peculiarities of a particular plant, the first choice should always be based on cost of alloy at the required carbon level. Prior sound experience may justifiably alter this choice.

Steels for Case Hardening

The most used case hardening processes, carburizing, carbonitriding and cyaniding, and the steels commonly processed by them, are discussed in detail on pages 677 to 697 of the 1948 Handbook. To that information should be added the fact that many alloy steels are now specified on the basis of core hardenability. Although the same considerations generally apply as have been given for the selection of uncarburized grades, there are some peculiarities in carburizing applications.

First, in a case hardened steel the hardenability of both case and core must be considered. Because of the difference in carbon content, case and core have hardenabilities quite different; moreover, the two regions have different functions to perform in service. Until the introduction of lean alloy steels such as the 8100 series, with and without boron, there was little need to be concerned about case hardenability because the alloy content combined with high carbon content always provided adequate hardenability. Also, when the alloy content rose above 2%, the temperature range of martensite formation in the case was frequently lowered enough so that elaborate treatments were often necessary to combat the retention of excessive amounts of austenite.

With the use of lean alloy steels as a conservation measure in recent years, case hardenabilities have often been lower than those shown by alloy steels of 1 to 2% total alloy content, and instances of insufficient hardenability have been reported. Information on case hardenability is now accumulating but it is not yet sufficient to provide dependable data in summary form.

The hardenability of the steels as purchased will be the core hardenability. Because these low-carbon steels, as a class, are shallow-hardenining and because of the wide variation in the section sizes of case hardened parts, the hardenability of the steel must be related to some critical section of the part—for example, the pitch line or the

root of a gear tooth. This is done best by making a part of a steel of known hardenability, heat treating it and then, by means of equivalence of hardness, relating the hardenability in the critical section or sections to the proper positions on the end-quench hardenability specimen.

Core Hardness. Because of the complex and often severe service requirements of gears, the specification of core hardness is most often attempted for gear teeth. To the previous analysis of this problem (page 682, 1948 Handbook) can be added that the limiting factor for maximum core hardness appears to be the residual stress pattern. As the core hardness rises and approaches that of the case, the compressive stress in the case is reduced and may eventually become tensile. Such a condition is often the cause of tooth breakage at the root. These are not fatigue failures; instead they occur suddenly and are often of a brittle type, even though the steel is tough by all ordinary standards.

Such behavior makes it necessary to re-examine the time-honored idea that a case hardened part requires a tough core to prevent such failures. These failures start in the case, and the only effect "toughness" in the core could have would be on the rate of progress of the failure. While higher toughness in the core might slow the progress of fracture, it could not prevent such progress. Consequently, the proper combination of case depth, core hardness and treatment must be developed to provide a satisfactory residual stress pattern.

A common mistake is to specify too narrow a range of core hardness. When, as in good practice, the final quench is from a temperature high enough to allow the development of full core hardness, the hardness variation at any location will be that of the hardenability band of the steel at the corresponding position on the end-quenched hardenability specimen. There is no known way to alter this state of affairs. In the commonly used alloy steels containing a maximum of 2% total alloy content, the range for the core hardness of sections such as gear teeth is 12 to 15 points Rockwell C. Higher-alloy steels exhibit a narrower range; for example, in 4815 the range is 10 points and in 3310 it is 8 points. Such steels are justified only for severe service or special applications.

Thus the selection of steels for case hardening applications is more complex than for others. In addition to the factors already mentioned, there are highly variable conditions in heat treating and sometimes differences of opinion, even among qualified engineers. The subject can be simplified to some extent by dividing it into applications involving (1) gears and similar parts and (2) all other applications.

Gears are almost always oil quenched because distortion must be held to the lowest possible level. This means that alloy steels are usually selected—which particular alloy is much debated. The lower-alloy steels such as 4023, 51xx-H, 4118, 86xx-H and 4620-H, with a carbon range between 0.15 and 0.25%, are in wide use and are generally satisfactory. The first choice would usually be made from the last two steels mentioned, as either should be safe for all

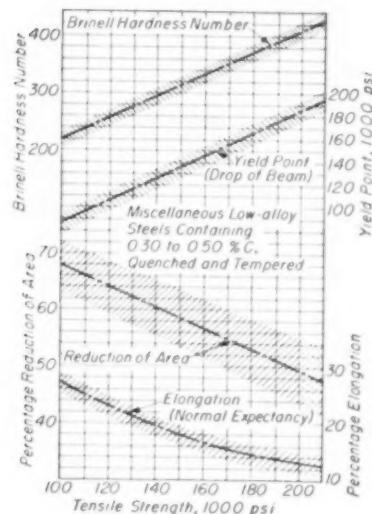


Fig. 10. Most Probable Mechanical Properties of Tempered Martensite (Patton)

lected on the basis of the lowest cost steel that provides the required hardenability and behaves satisfactorily in processing. It may not be inferred that all tempered martensites of the same hardness are alike in all respects. The lower reduction of area values for plain carbon martensite have been pointed out. A further difference, sometimes important, is that fully quenched alloy steels require, for the same hardness levels, higher tempering temperatures than carbon steel. This temperature difference may be presumed to reduce the residual stress level in finished parts.

There are important differences in machinability, too. In the alloy steels it has been demonstrated that, other things being equal, those martensites containing nickel, chromium and molybdenum machine better than others when the hardness is 300 Brinell or more. Carbon steels machine satisfactorily up to about 300 Brinell, but above

ordinary applications. The final choice, based on service experience or dynamometer testing, should be the lowest-cost steel that will do the job. To this list should be added C-1024 which, although not classed commercially as an alloy steel, has sufficient manganese to make it oil-quenching up to an end-quench correlation point of 3/16. For heavy-duty applications higher-alloy grades such as 4320-H, 4817-H, 2515-H, 3310-H and 9310-H are justifiable if based on actual performance tests. Life testing of gears in the same mountings used in service, to prove both the design and the steel selection, is particularly important for heavy-duty applications.

The carbonitriding process extends the use of carbon steels such as 1016, 1018, 1019 and 1022 into the field of light-duty gearing because it makes the case oil-quenching in teeth 8 diametral pitch and finer. Steels selected for such application should be specified silicon killed, fine grain, to insure uniform case hardness and dimensional control. The core of such gears will, of course, have the properties of low-carbon steel, oil quenched. In the thin sections of fine-pitch teeth this may be up to Rockwell C 25. The carbonitriding process is usually limited for economic reasons to maximum case depths of approximately 0.025 in. For additional information, see the article herein entitled "Carbonitriding".

In Other Applications, case hardened steels follow the rules previously set forth for steel selection in general. When distortion is not a controlling factor, the carbon steels described above, water quenched, can be used up to 2 in. diam. In larger sizes, low-alloy steels, water quenched, such as 5120, 4023, and 6120, can be used but distortion and quench cracking must be guarded against. When considerable machining is done, the free-cutting steels, 1117 and 1118, are often used. In oil quenching after conventional carburizing, 1117 will produce full hardness of case in sizes up to $\frac{3}{4}$ in. diam, and 1118 up to $1\frac{1}{2}$ in.; after carbonitriding the limits are approximately 1 and 2 in. diam, respectively.

In those numerous applications where the service is not severe, these free-cutting steels provide the advantageous combination of low cost, ease of machining and oil quenching for low distortion. Hydraulic pump parts are a good example. More severe service such as the races for needle bearings in accessory drives usually require alloy steels for the necessary combination of case and core properties to withstand the compressive loads. Steels such as 4023 and 6120 are useful up to 1-in. section and 8620-H, 8720-H and 4620-H up to 2-in.

When low-carbon stampings and upset parts are to be case hardened, the steel must satisfy opposing requirements and is selected primarily for cold workability. Sheet and plate are customarily made of rimmed steel; steel for upsetting is rimmed or semi-killed. These steels have low manganese, low silicon, and no grain size control; consequently, their case hardening characteristics are poor. With conventional carburizing or cyaniding, water quenching, although accompanied by distortion troubles, is usually necessary to produce full case hard-

ness; even then, there may be soft spots. Because of the nitrogen introduced in the process, carbonitriding provides full case hardness with oil quenching in these steels in moderately heavy sections. Thus a heat treating process can solve a troublesome problem in steel selection.

The highly alloyed steels such as 4320-H, 4817-H, 2515-H, 3310-H and 9310-H, besides being used in heavy-duty gearing, are employed in specialized machinery such as oil-well drilling equipment, aircraft engines and earth-moving equipment, where lower alloy content will not produce a satisfactory part.

Availability of Steels

All of the steels discussed here are produced commercially in significant but far from equal quantities. Although this is true of the United States and Canada as a geographic unit, it does not imply that all grades are made in all steel-producing districts. However, with the exception of the South and the far West, most grades will be available from some mill. If production requirements are such that the grade selected should be purchased in mill-heat quantities or more, there is no problem of availability when the market is free. Since less than heat quantities must often be purchased, availability on that basis must be considered.

Table V. Representative Steels Available from Warehouses

Finish and Steel Size ^(a)	Remarks
1015.. HR to 3 in.	Merchant quality
1018.. HR and CF full range	Semi-killed to 3 in. Silicon-killed over 3 in.
1117.. HR and CF full range	Semi-killed
1141.. CF; small amount HR	...
1144.. CF only	...
1042.. HR and CF full range	...
4142.. HR and CF full range	Can be used by selection for 4140 to 4150
4615.. HR only	...
8620.. HR and CF full range	...
8642.. HR and many sizes CF	Can be used by selection for 8640 to 8650
4340.. HR annealed 3 to 6 in.	...

(a) HR means hot rolled; CF, cold finished

The mill representatives are the best source of information about the grades most often produced in any district so that orders for partial heats have the best chance of being filled quickly.

Warehouse Steels. The availability from warehouses is naturally more limited than from the producing mills because of the inventory problem and because warehouse trade requirements are a reflection of small-lot rather than large-lot consumption in the area they serve. While the grades available follow a certain general pattern, there will be considerable variation in different parts of the country. Table V shows a representative list of grades available from warehouses in the central part of

the United States. Whenever warehouse availability is an important consideration in steel selection, inquiry should be made of the local sources for exact information, both because of geographic location and because warehouse demand is constantly changing as prices and technology change.

Plant Standardization of Steels

If a steel for each of many parts is selected on the basis of the exact requirements of each part alone, many kinds of steel will be specified for the total list of parts. If all of the parts are to be produced in large quantity, it may be entirely practical to have each part made from a different steel. But since this is usually not true, extreme individualism in steel selection for each part can lead to serious problems because of small usage of some or all items. These problems start with purchasing considerations of availability and cost. The cost per ton of small quantities is appreciably higher than for large quantities. Then there are storage and inventory problems because of the larger number of items to be stocked, plus added chances of mistakes in distributing the steel within the plant. Finally, there is the variation in heat treating procedures required by the individual steels.

The other extreme is to make all parts from the same size and grade of steel. This is obviously impossible in all but very rare circumstances.

The practical answer is to standardize on the fewest grades necessary to satisfy plant-wide usage at the lowest cost. This means that not all requirements will be met in equal degree; some compromises will be necessary. First, the engineering requirements must be met fully after critical examination and changes in the interest of standardization or cost reduction. Next come the machining requirements. If parts are not to be fed through collet chucks, the size variation in hot rolled steel will not be troublesome, but if collet chucks are used, the closer size tolerance of cold finished steels is usually necessary. Other advantages of the close sizing of cold finished steels have been discussed previously.

If carbon steels are to be used and the parts require extensive machining, the appropriate free-machining grade from the 11xx or 12xx series should be specified as its extra cost will be more than repaid by the increased production. These steels should be specified cold drawn because the full machining advantage of free-cutting steels results from a combination of their composition and the work of cold drawing. Obviously, if only small amounts of machining are to be done, such as cutting-off and drilling a cotter-pin hole at one end, free-cutting steels would not be economical. If the piece is to become part of a welded assembly, the high sulfur content of free-cutting steels will be bothersome. If heat treating is to be done, silicon-killed carbon steels with a minimum of 0.60% Mn and controlled grain size are much to be desired because of more uniform behavior, but in the low-carbon varieties their cost is higher than semi-killed steels with lower manganese content.

The above are some, but by no means all, of the factors that may have to be

considered in selection and standardization of the fewest grades.

Standardization of 1-In. Bars. The following example illustrates what was accomplished in one plant where 31 parts were being made from 1-in. diam bar stock, utilizing ten different steels. When part prints were examined and the proposed new plan of manufacture discussed with the Processing Department, it was found, as would be expected, that the forged parts listed in the first two groups in Table VI should be made of hot rolled steel and the remainder of these groups, not forged, could most economically use steel with the same finish. (Either processing or strength considerations, or both, required eight of the 31 parts to be made of cold drawn steel, listed in group 3.)

Design considerations required that three parts in the hot rolled group be a case hardened alloy steel. Past production experience with similar models had shown that a number of alloy steels could be used but some were more acceptable than others from a machining standpoint. 8620-H had not been among the steels previously used but from a consideration of its hardenability, plus favorable shop experience with this grade on other parts, it was decided that it would be satisfactory for two of the shafts but that 8625-H would be required for the third one. This particular alloy combination was high on the availability list and cheap. After the initial selection, production experience and dynamometer testing of the gears showed that the 8625-H could be replaced with 8620-H, resulting in standardization on one hot rolled alloy steel as shown in group 2.

The strength required of the remainder of the hot rolled parts indicated that 1045 was necessary for all those not heat treated, except the tie rod; 1045 could also be used to meet the requirements of the heat treated parts. It was decided to make the tie rod also from C-1045 in the interest of both standardization and cost reduction. The cost of C-1045 purchased from a mill is less than that of a lower-carbon steel purchased in small quantities from a warehouse. This decision eliminated one grade from inventory.

When considering the strength requirements of the cold finished group, it became evident that some parts required a higher minimum strength level than could be obtained from ordinary cold drawn C-1045. For these parts (Table VI, group 3) a cold drawn steel with guaranteed minimum mechanical properties was adopted. C-1045 was used instead of C-1141 because the amount of machining on the parts did not warrant the extra cost of the free-cutting grade.

The parts in this group to be case hardened had core strength requirements compatible with plain carbon steel, silicon killed, fine grain. A free-cutting steel was needed and C-1117 was adopted. To this group were added the remainder of the parts for which free-cutting steel could be used to advantage, thus making up group 4.

The remainder of the cold finished parts, group 5, required neither special strength nor heat treatment; 1018, cold drawn, was adopted. This steel costs the same as 1020 but because of its higher manganese content it has slightly better machinability and is car-

ried as a general-purpose, low-carbon, cold drawn steel. It has advantages over C-1020 in case hardening. While no parts in this 1-in. size group require this heat treatment, parts in other size groups do, and it is convenient to have one general-purpose steel on hand.

Originally ten steels were specified in 1-in. round; this came about partly from blind copying of the steels used in older designs but principally from a study of each part separately, without regard for the over-all needs. The previous steels were 4620, 5145, 4140, 1045 HR, 1045 CF, 1020 CF, 1035 CF, 1040 HR, 1120 CF and 1025 HR. Standardization, with the needs of both engineering and manufacturing in mind, and with close attention to costs, reduced the list to the five steels shown in Table VI.

The processing equipment available played an important part in the standardization. The through-hardening alloy steels 5145 and 4140 could be replaced with water-quenched carbon steel only because efficient water quenches were available. It is true that the strength specified for the heat treated alloy steel was low and in that sense the alloy steel represented over-specification, but the fact remains that it took modern quenching equipment to permit an economical replacement.

The availability of carbonitriding equipment made it possible to use C-1117 for all the case hardened parts except gears at a considerable saving in both steel and processing cost. For parts requiring low distortion in heat treatment, an oil-quenching alloy steel

was unnecessary because the addition of nitrogen in carbonitriding made the case of the carbon steel oil-hardenable. The processing economy arose from the fact that finish grinding stock could be considerably reduced because of the low distortion.

The choice of alloy carburizing steel was made, in part, on the basis that equipment particularly suitable for direct quenching would be available. Among other things, this equipment permitted close control of the quenching temperature. Had the equipment been less suitable to this type of operation, another steel, perhaps 4620-H, might have been chosen because its high nickel content provides more leeway in quenching temperature. The result would have been higher steel cost. As it was, a reduction in steel cost was used to help amortize the cost of new equipment. It must be emphasized again that the standardization, particularly as it is affected by processing requirements, would probably be different for a different plant.

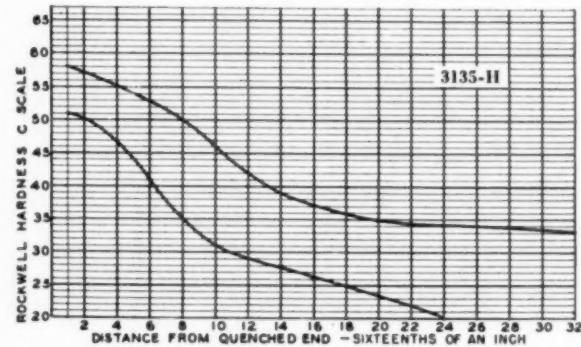
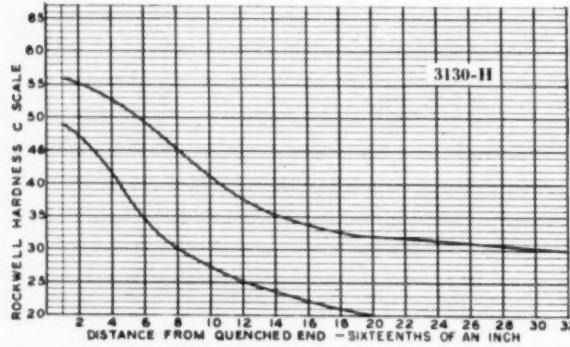
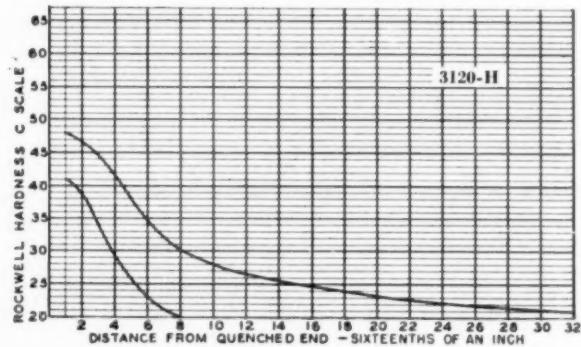
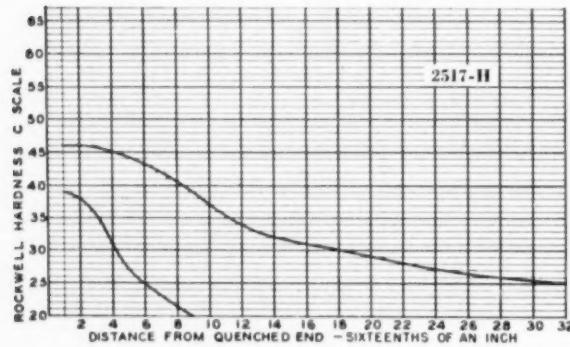
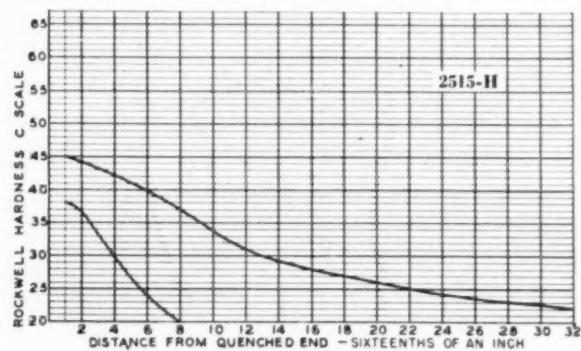
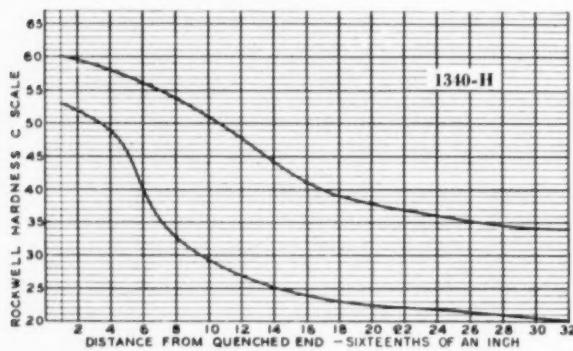
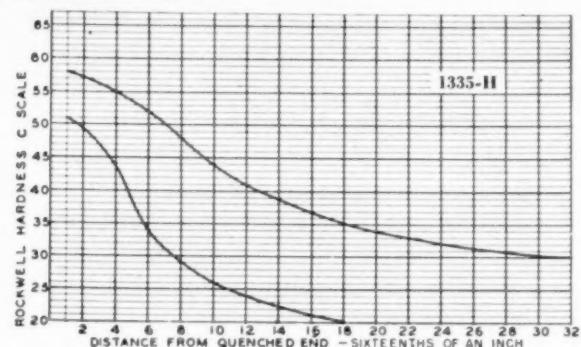
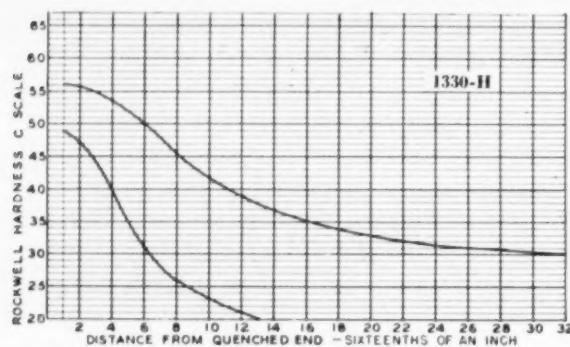
All standardization is limited by certain rigid requirements that determine the minimum number of grades which may be specified. The maximum number of grades specified is determined by how many compromises may be made in meeting the less rigid requirements to fit steels to the minimum grouping.

Hardenability bands and chemical compositions for the 79 standard SAE-AISI H-steels are shown on the next ten pages.

Table VI. Standardized List of Parts for Stock 1 In. in Diameter

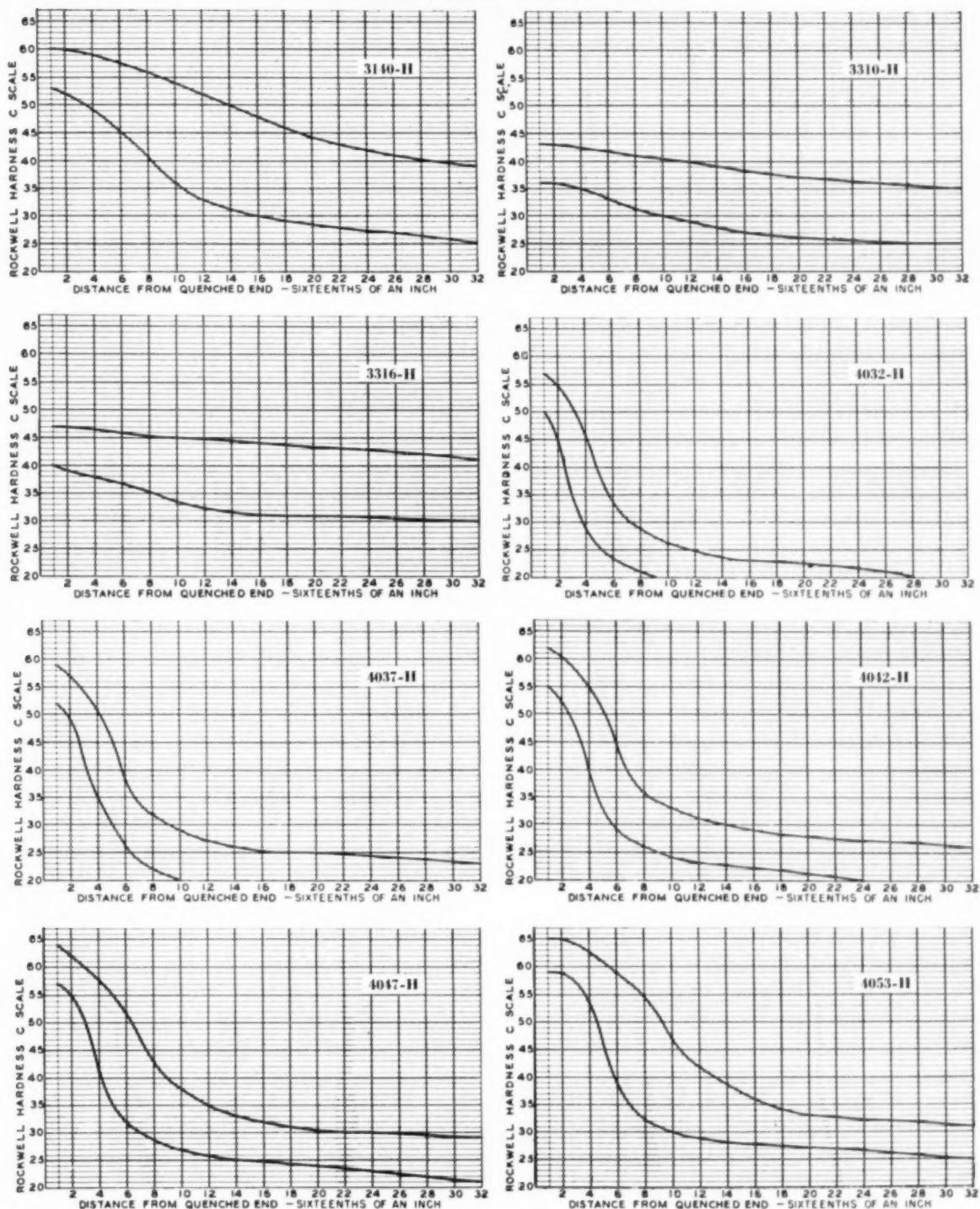
Part	Pounds per Piece	Monthly Production	Remarks
Group 1—Hot Rolled Carbon Steel (C-1045, silicon-killed, fine grain)			
Spindle Shaft			
Shaft	3.84	750	90,000 psi min yield strength, welded
Tie Rod	22.93	Service	25,000 psi min yield strength
4th Speed Shifter Fork	2.3	Service	Forging; 35,000 psi min yield strength
Spindle Ext.	3.15	Special	35,000 psi min yield strength, welded
Shaft	3.84	9000	90,000 psi min yield strength
Group 2—Hot Rolled Alloy Steel (8620-H)			
Shaft and Gear	6.00	4000	Case hardened, part of final drive
Pinion Shaft	5.79	500	Case hardened, part of power train
Pinion Shaft	21.04	6000	Case hardened, part of final drive
Group 3—Cold Drawn Steel, Guaranteed Minimum Properties (C-1045, cold drawn, 100,000 psi min tensile strength, 80,000 psi min yield strength, 15% min elongation in 2 in., 40% min reduction of area)			
Stud, Special	2.291	Service	80,000 psi min yield strength
Stud, Special	2.043	Service	80,000 psi min yield strength
Shaft, Clutch Drive	6.313	3650	80,000 psi min yield strength
Shaft	5.60	Service	80,000 psi min yield strength
Shaft, Special	3.7402	350	80,000 psi min yield strength
Shaft, Steering	6.404	5400	80,000 psi min yield strength
Shaft, Spined	4.638	900	80,000 psi min yield strength
Shaft, Coupling	4.508	Special	80,000 psi min yield strength
Group 4—Free-Cutting Steel (C-1117, silicon-killed, fine grain)			
Valve Lever Shaft Collar	0.368	Service	No special strength required
Bushing	0.636	Service	No special strength required
Oil Seal	0.3157	6000	No special strength required
Roller	0.460	500	Carbonitrided
Roller, Cam Follower	0.42067	15000	Carburized
Washer	0.23685	3600	No hardness requirement
Shaft, Drive Gear	2.42	5600	Case hardened, heavily loaded
Shaft, Brake Cross	21.724	Service	50,000 psi min yield strength
Shifter Guide	2.097	Service	No strength requirements
Spacer, Wheel Guard	0.313	Service	No strength requirements
Bushing	1.25	Service	Carbonitrided
Brake Cross Shaft Brkt.	0.375	2450	No special requirements
Group 5—General-Purpose Cold Drawn Steel (C-1018)			
Shaft, Steering	1.29	Service	50,000 psi min yield strength
Shaft, Drive	16.83	4300	50,000 psi min yield strength
Shaft, Coupling	9.2582	850	50,000 psi min yield strength

Hardenability Bands, 1330-H to 3135-H



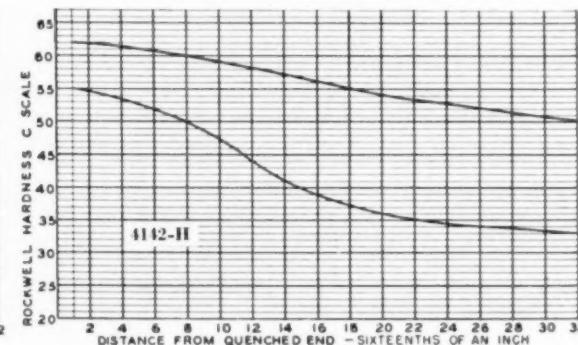
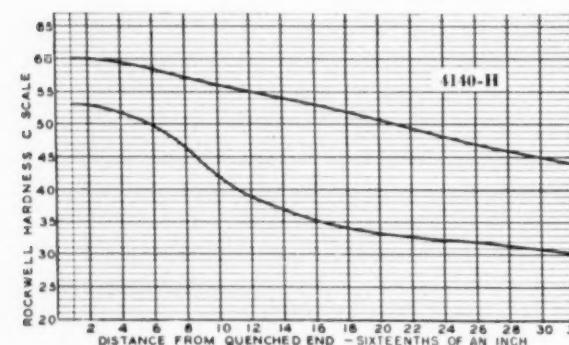
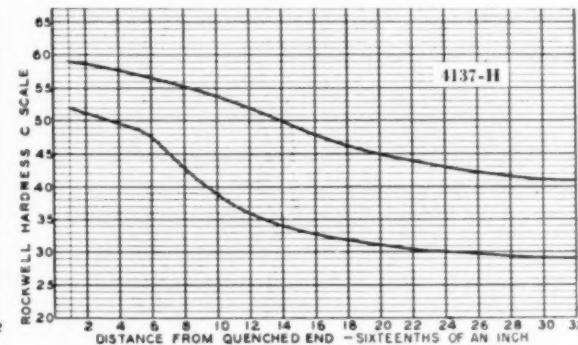
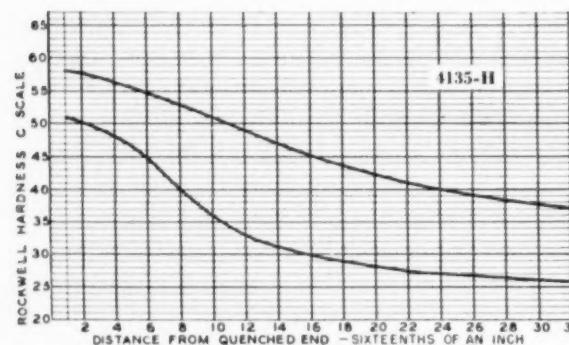
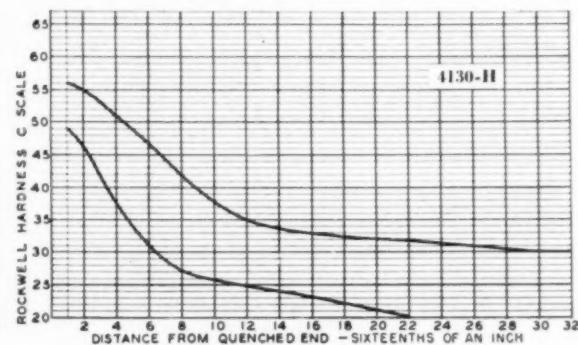
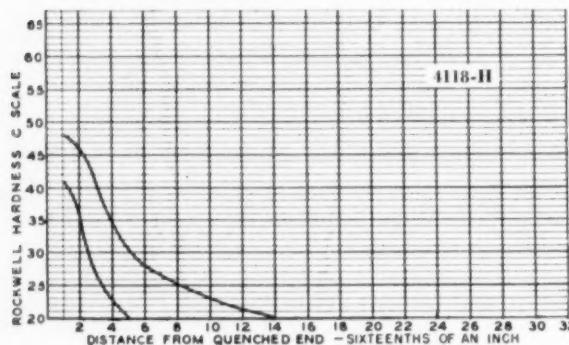
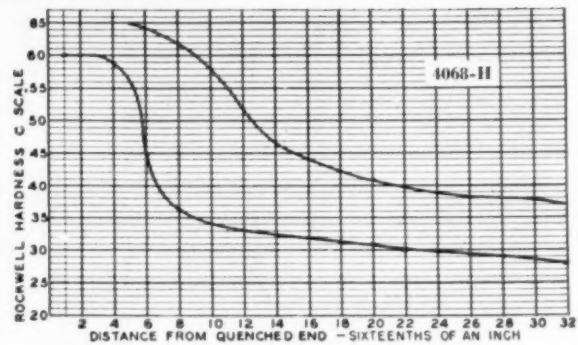
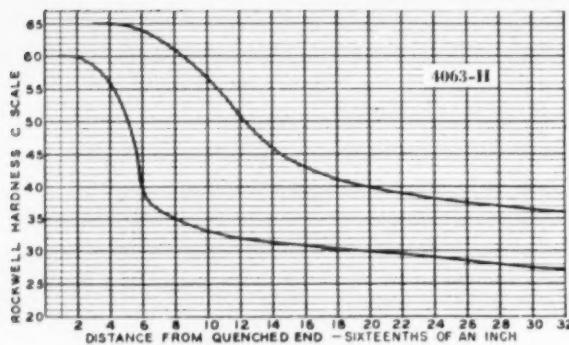
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
1330-H	0.27 to 0.33	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1650	1600
1335-H	0.32 to 0.38	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1600	1550
1340-H	0.37 to 0.44	1.45 to 2.05	0.20 to 0.35	.....	.....	.....	1600	1550
2515-H	0.12 to 0.18	0.30 to 0.70	0.20 to 0.35	4.70 to 5.30	.....	.....	1700	1550
2517-H	0.14 to 0.20	0.30 to 0.70	0.20 to 0.35	4.70 to 5.30	.....	.....	1700	1550
3120-H	0.17 to 0.23	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1700	1550
3130-H	0.27 to 0.33	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1650	1600
3135-H	0.32 to 0.38	0.50 to 0.90	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1600	1550

Hardenability Bands, 3140-H to 4053-H



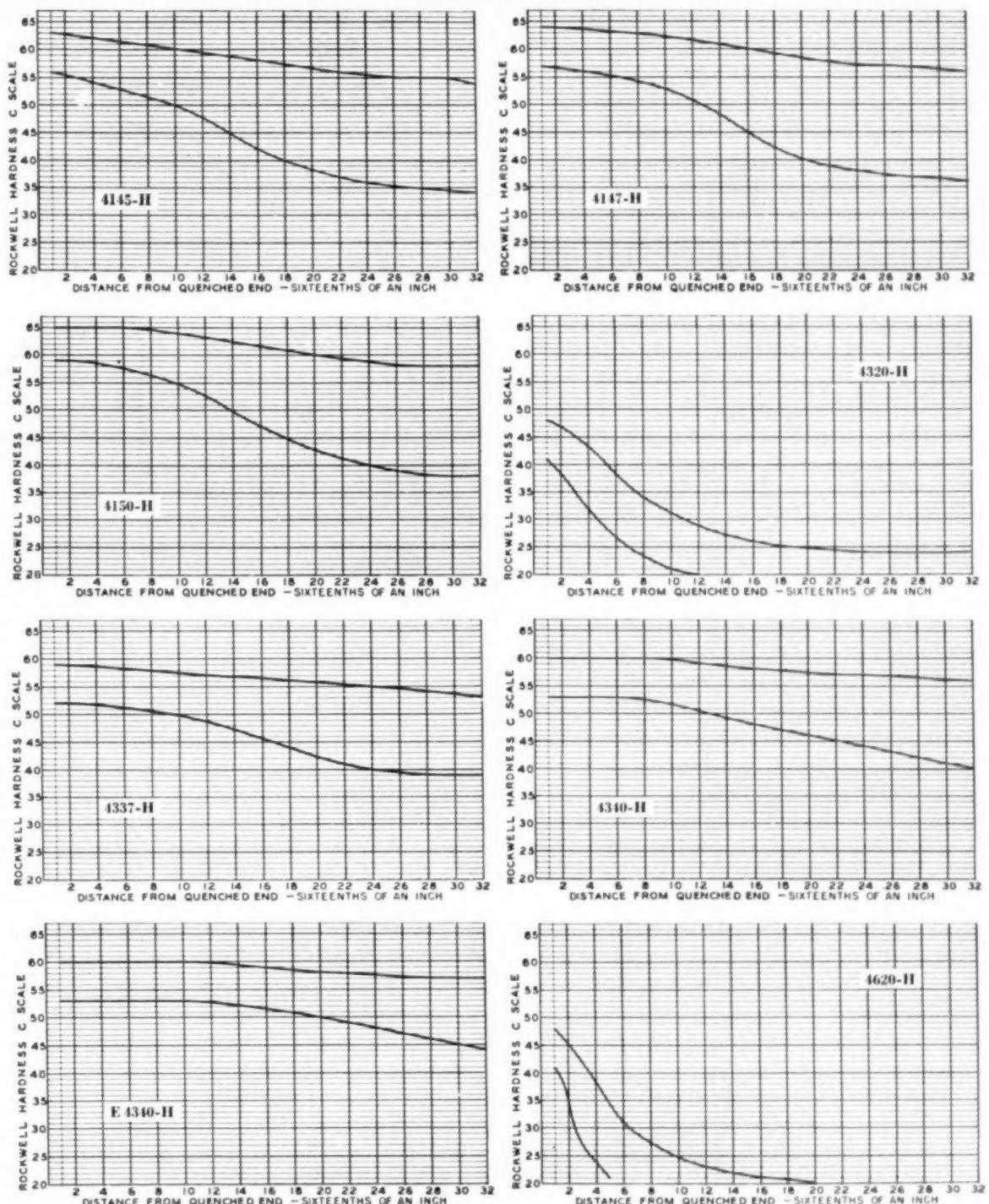
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
3140-H	0.37 to 0.44	0.60 to 1.00	0.20 to 0.35	1.00 to 1.45	0.45 to 0.85	.....	1600	1550
3310-H	0.07 to 0.13	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	1.30 to 1.80	.....	1700	1550
3316-H	0.13 to 0.19	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	1.30 to 1.80	.....	1700	1550
4032-H	0.29 to 0.35	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1650	1600
4037-H	0.34 to 0.41	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4042-H	0.39 to 0.46	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4047-H	0.44 to 0.51	0.60 to 1.00	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4053-H	0.49 to 0.56	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550

Hardenability Bands, 4063-H to 4142-H



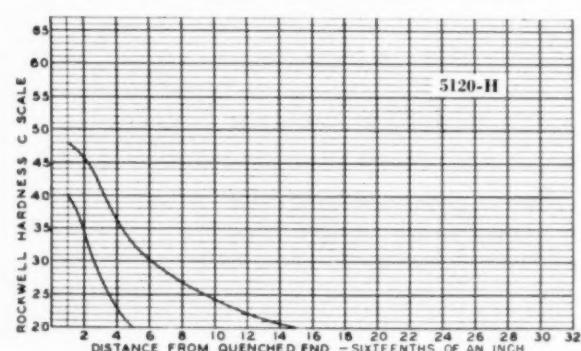
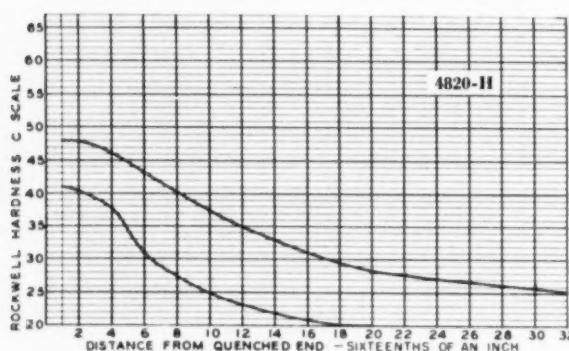
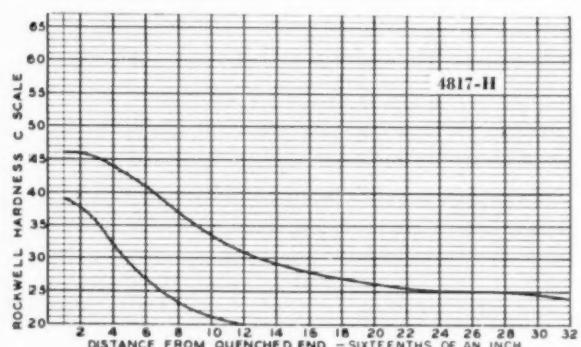
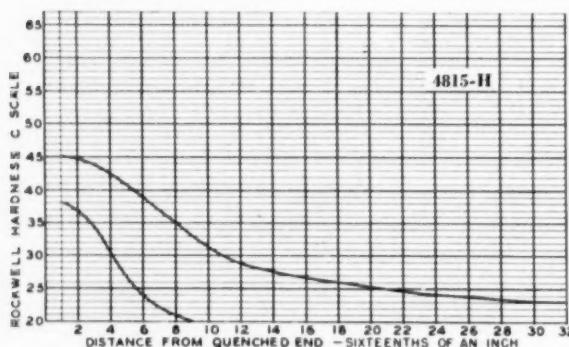
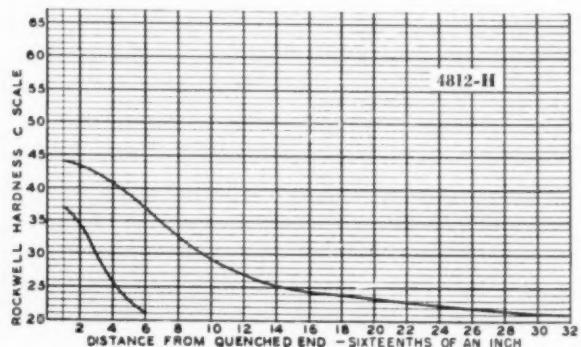
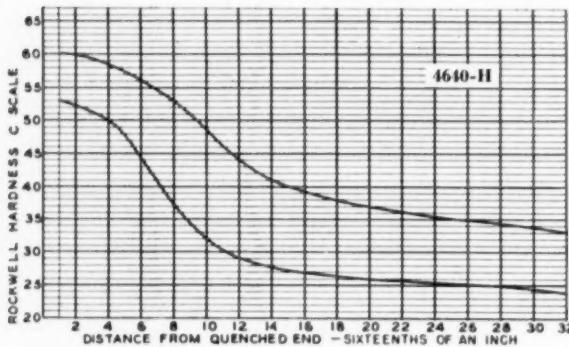
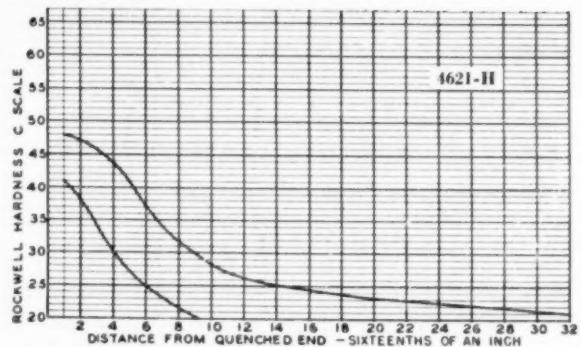
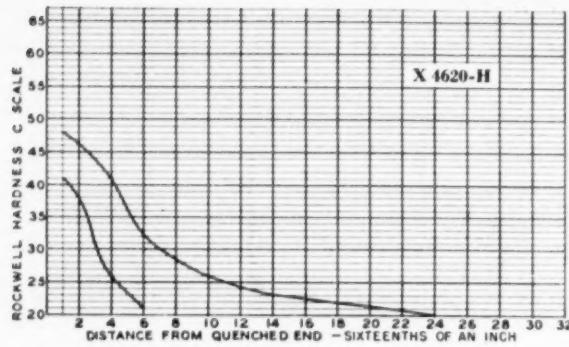
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
4063-H	0.59 to 0.69	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4068-H	0.62 to 0.72	0.65 to 1.10	0.20 to 0.35	.....	.....	0.20 to 0.30	1600	1550
4118-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.30 to 0.70	0.08 to 0.15	1700	1700
4130-H	0.27 to 0.33	0.30 to 0.70	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1650	1600
4135-H	0.32 to 0.38	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4137-H	0.34 to 0.41	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4140-H	0.37 to 0.44	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4142-H	0.39 to 0.46	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550

Hardenability Bands, 4145-H to 4620-H



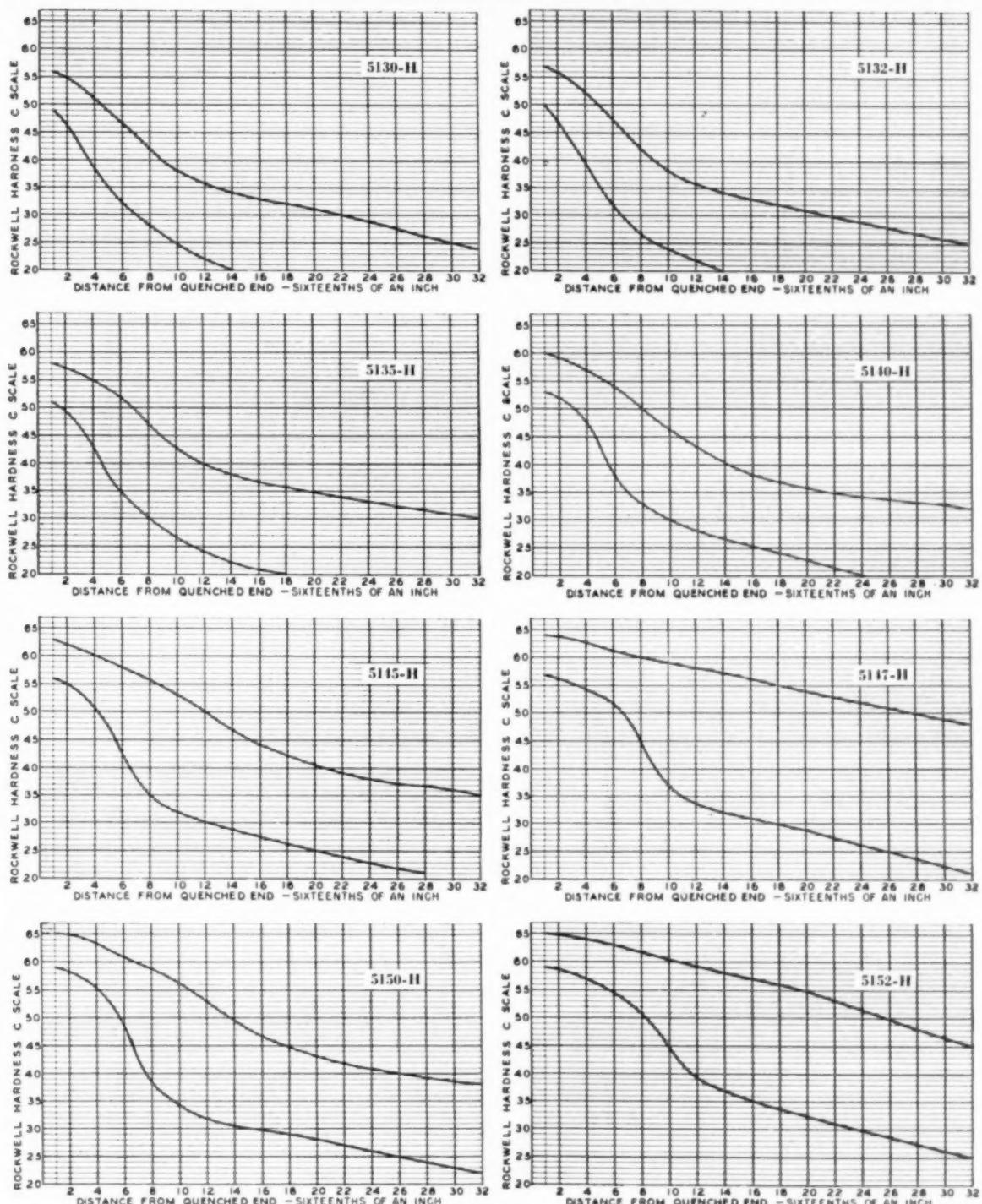
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
4145-H	0.42 to 0.49	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4147-H	0.44 to 0.51	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4150-H	0.47 to 0.54	0.65 to 1.10	0.20 to 0.35	.....	0.75 to 1.20	0.15 to 0.25	1600	1550
4320-H	0.17 to 0.23	0.40 to 0.70	0.20 to 0.35	1.55 to 2.00	0.35 to 0.65	0.20 to 0.30	1700	1700
4337-H	0.34 to 0.41	0.55 to 0.90	0.20 to 0.35	1.55 to 2.00	0.65 to 0.95	0.20 to 0.30	1600	1550
4340-H	0.37 to 0.44	0.55 to 0.90	0.20 to 0.35	1.55 to 2.00	0.65 to 0.95	0.20 to 0.30	1600	1550
E 4340-H	0.37 to 0.44	0.60 to 0.95	0.20 to 0.35	1.55 to 2.00	0.65 to 0.95	0.20 to 0.30	1600	1550
4620-H	0.17 to 0.23	0.35 to 0.75	0.20 to 0.35	1.55 to 2.00	0.20 to 0.30	0.20 to 0.30	1700	1700

Hardenability Bands, X4620-H to 5120-H



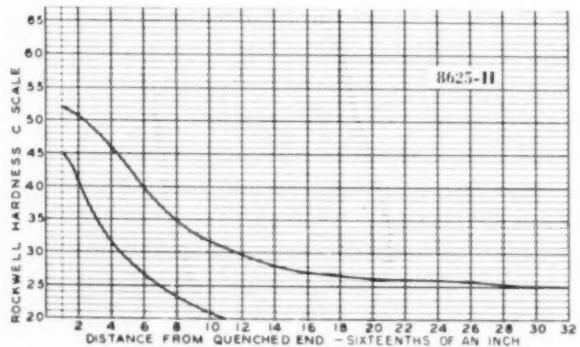
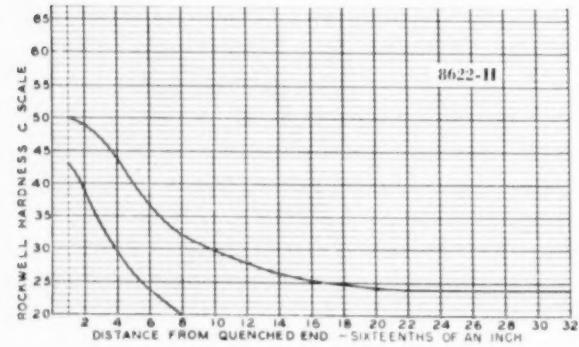
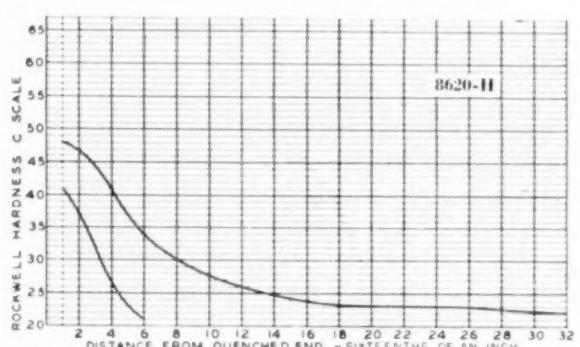
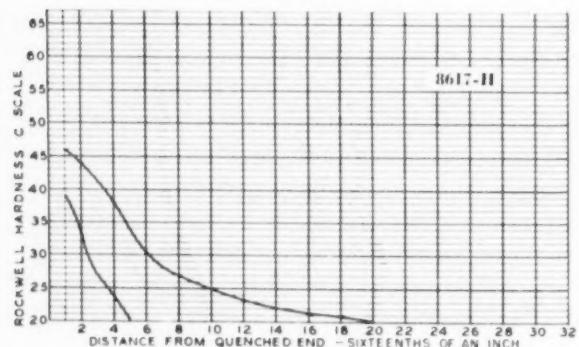
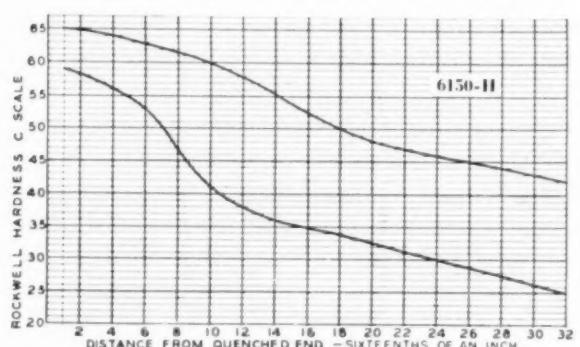
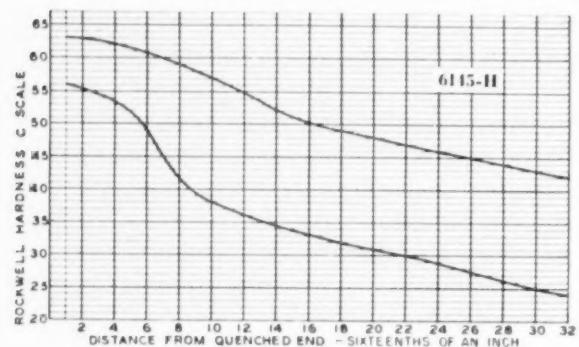
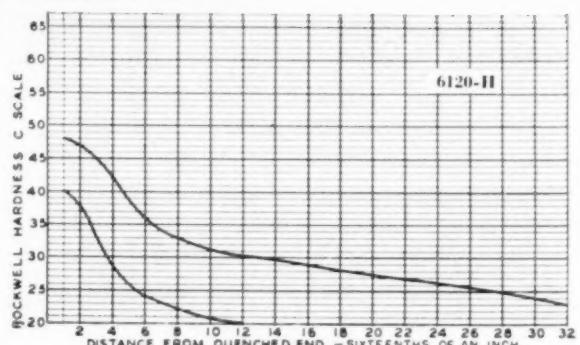
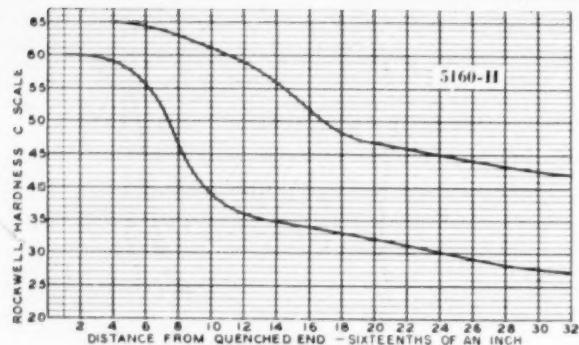
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
X4620-H	0.17 to 0.23	0.40 to 0.80	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1700	1700
4621-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1700	1700
4640-H	0.37 to 0.44	0.50 to 0.90	0.20 to 0.35	1.55 to 2.00	.....	0.20 to 0.30	1650	1600
4812-H	0.09 to 0.15	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
4815-H	0.12 to 0.18	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
4817-H	0.14 to 0.20	0.30 to 0.70	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
4820-H	0.17 to 0.23	0.40 to 0.80	0.20 to 0.35	3.20 to 3.80	.....	0.20 to 0.30	1700	1550
5120-H	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1700	1700

Hardenability Bands, 5130-H to 5152-H



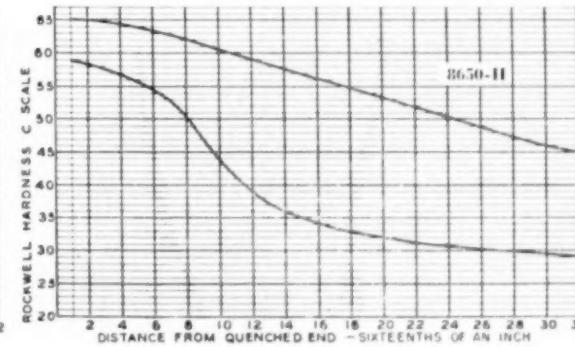
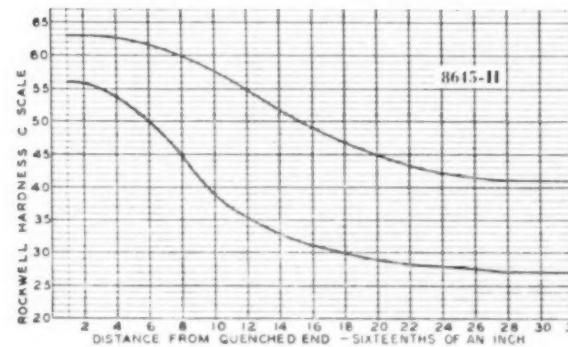
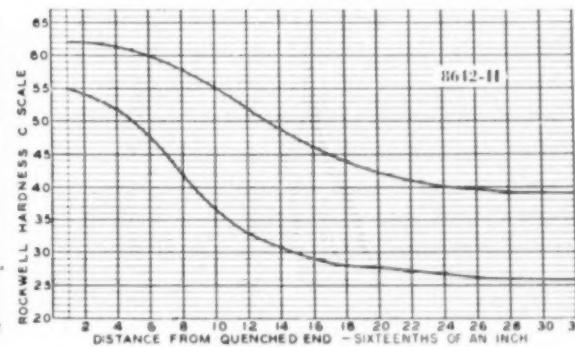
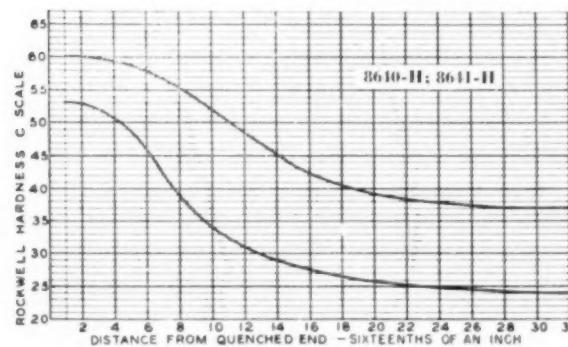
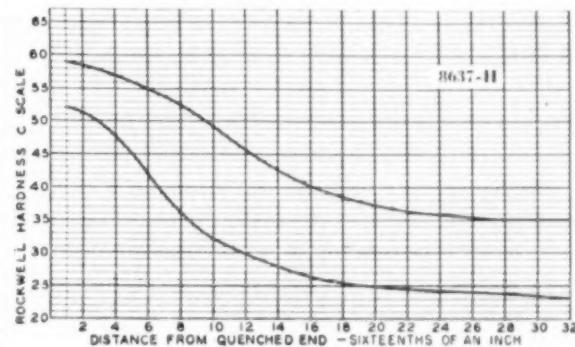
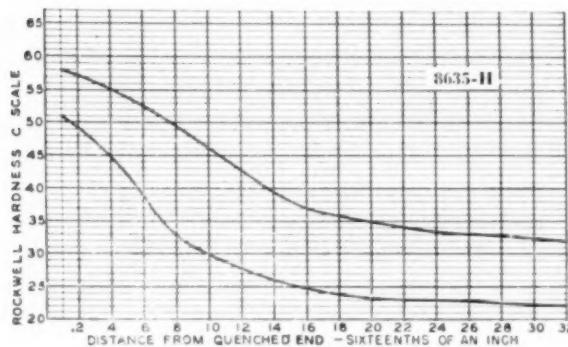
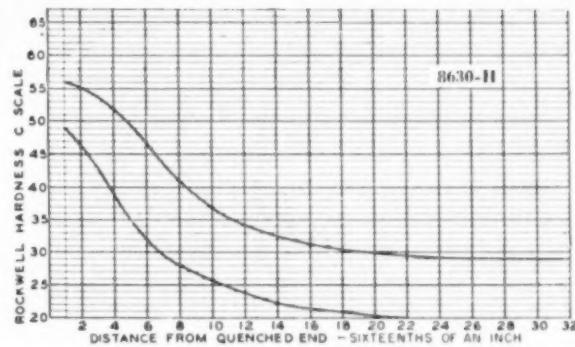
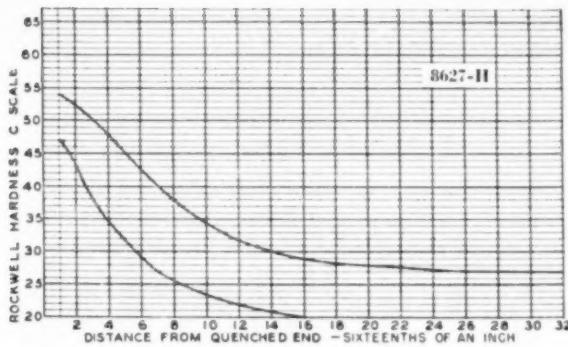
AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
5130-H	0.27 to 0.33	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	.....	1650	1600
5132-H	0.29 to 0.35	0.50 to 0.90	0.20 to 0.35	.....	0.65 to 1.10	.....	1650	1600
5135-H	0.32 to 0.38	0.50 to 0.90	0.20 to 0.35	.....	0.70 to 1.15	.....	1650	1600
5140-H	0.37 to 0.44	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5145-H	0.42 to 0.49	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5147-H	0.45 to 0.52	0.60 to 1.05	0.20 to 0.35	.....	0.80 to 1.25	.....	1600	1550
5150-H	0.47 to 0.54	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
5152-H	0.48 to 0.55	0.60 to 1.00	0.20 to 0.35	.....	0.85 to 1.30	.....	1600	1550

Hardenability Bands, 5160-II to 8625-II



AISI-SAE	C	Mn	Si	Ni	Cr	Mo or V	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
5160-II	0.55 to 0.65	0.65 to 1.10	0.20 to 0.35	.....	0.60 to 1.00	.....	1600	1550
6120-II	0.17 to 0.23	0.60 to 1.00	0.20 to 0.35	.....	0.60 to 1.00	0.10 min V	1700	1700
6145-II	0.42 to 0.49	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 min V	1650	1600
6150-II	0.47 to 0.54	0.60 to 1.00	0.20 to 0.35	.....	0.75 to 1.20	0.15 min V	1630	1600
8617-II	0.14 to 0.29	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25 Mo	1700	1700
8620-II	0.17 to 0.23	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25 Mo	1700	1700
8622-II	0.19 to 0.25	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25 Mo	1700	1700
8625-II	0.22 to 0.28	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25 Mo	1650	1600

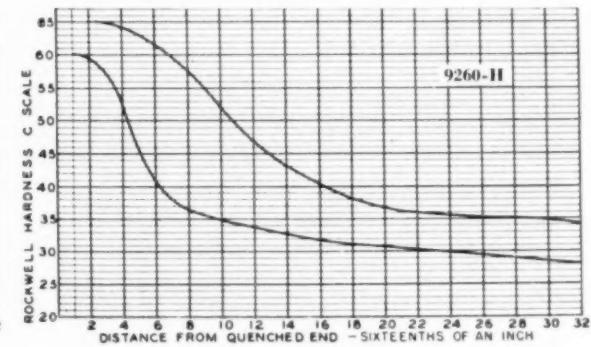
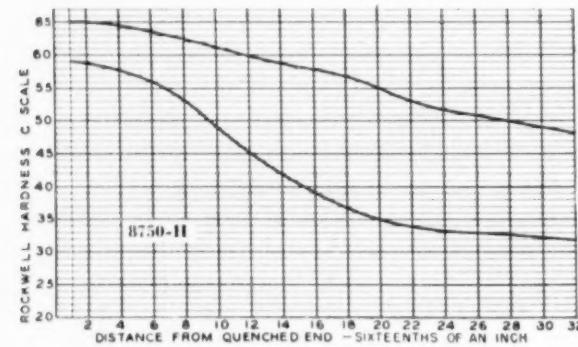
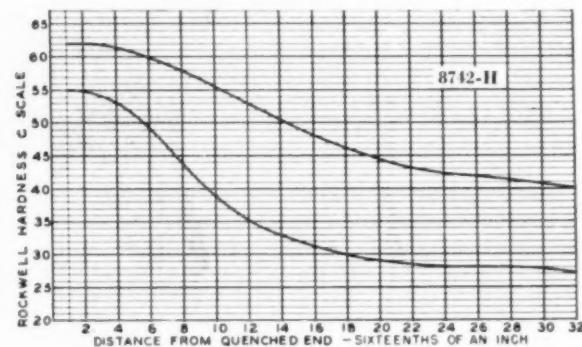
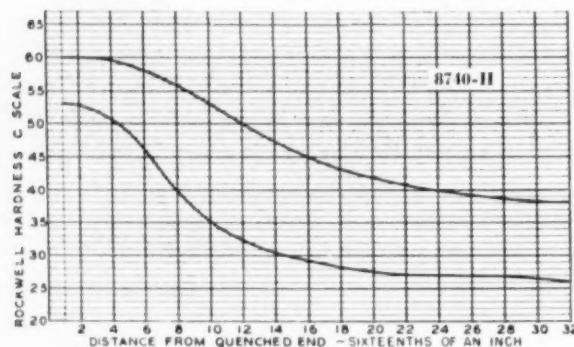
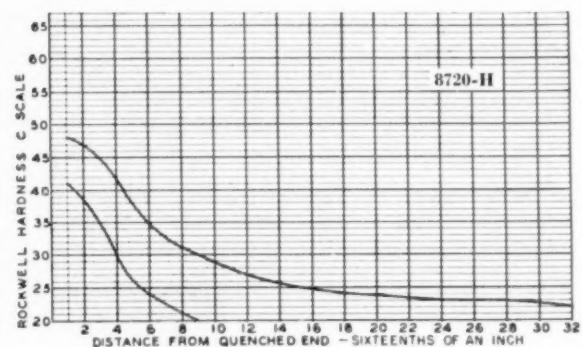
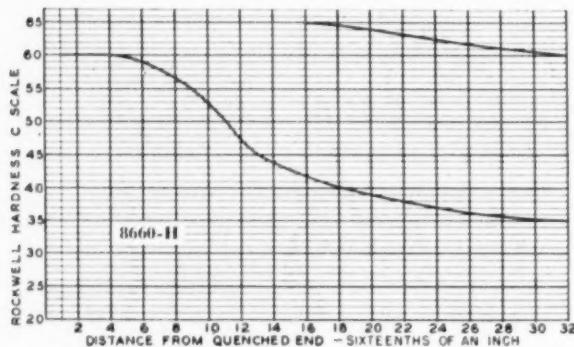
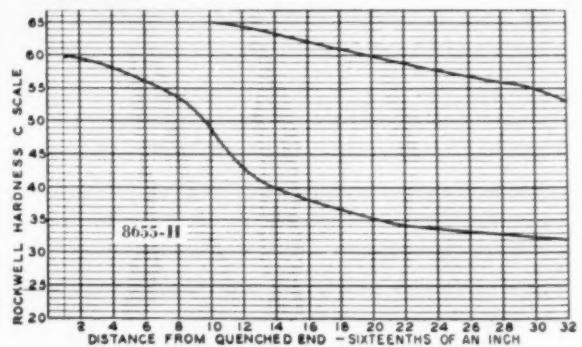
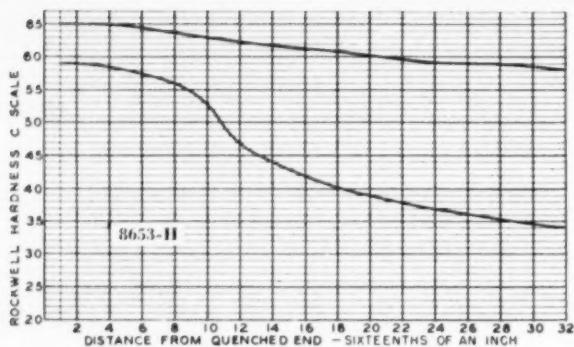
Hardenability Bands, 8627-H to 8650-H



AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
8627-H	0.24 to 0.30	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1650	1600
8630-H	0.27 to 0.33	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1650	1600
8635-H	0.32 to 0.38	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8637-H	0.34 to 0.41	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8640-H	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8641-H ^(a)	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8642-H	0.39 to 0.46	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8645-H	0.42 to 0.49	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8650-H	0.47 to 0.54	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550

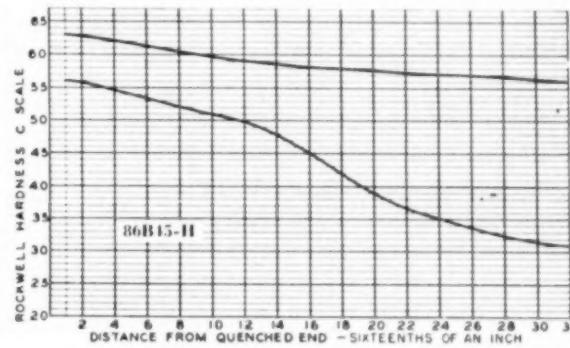
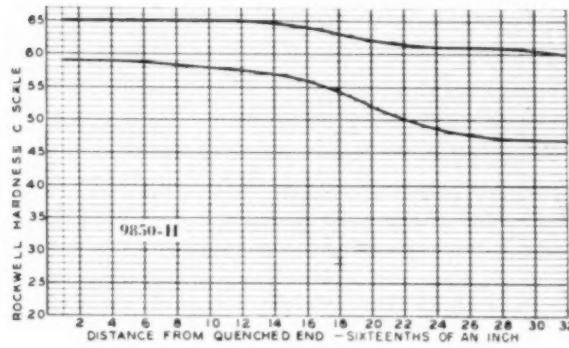
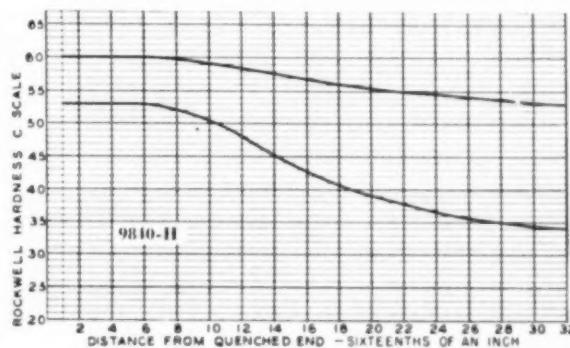
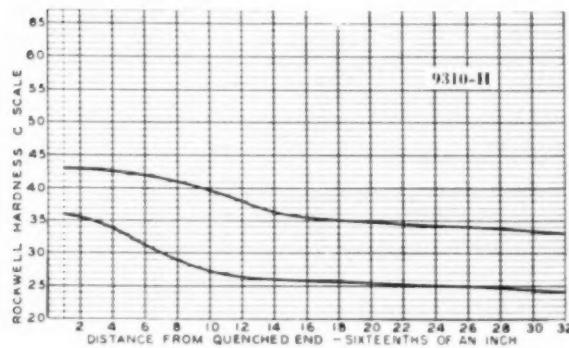
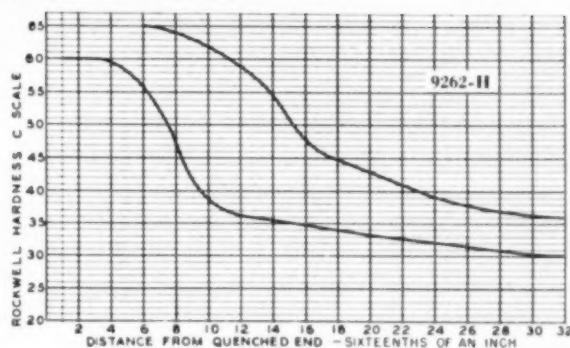
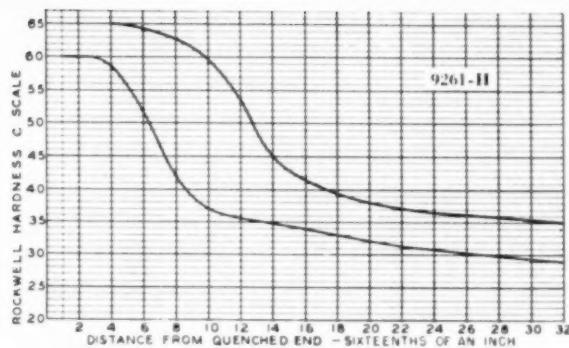
(a) Sulfur content 0.040 to 0.060%.

Hardenability Bands, 8653-II to 9260-II



AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
8653-II	0.49 to 0.56	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.50 to 0.85	0.15 to 0.25	1600	1550
8655-II	0.50 to 0.60	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8660-II	0.55 to 0.65	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550
8720-II	0.17 to 0.23	0.60 to 0.95	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1700	1700
8740-II	0.37 to 0.44	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
8742-II	0.39 to 0.46	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
8750-II	0.47 to 0.54	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.20 to 0.30	1600	1550
9260-II	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	.....	.....	1650	1600

Hardenability Bands, 9261-H to 86B45-H



AISI-SAE	C	Mn	Si	Ni	Cr	Mo	Normalizing Temp, deg Fahr	Austenitizing Temp, deg Fahr
9261-H	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	0.05 to 0.35	.....	1650	1600
9262-H	0.55 to 0.65	0.65 to 1.10	1.70 to 2.20	.....	0.20 to 0.50	.....	1650	1600
9310-H	0.07 to 0.13	0.40 to 0.70	0.20 to 0.35	2.95 to 3.55	1.00 to 1.45	0.08 to 0.15	1700	1550
9640-H	0.37 to 0.44	0.60 to 0.95	0.20 to 0.35	0.80 to 1.20	0.65 to 0.95	0.20 to 0.30	1600	1550
9850-H	0.47 to 0.54	0.60 to 0.95	0.20 to 0.35	0.80 to 1.20	0.65 to 0.95	0.20 to 0.30	1600	1550
86B45-H ^(a)	0.42 to 0.49	0.70 to 1.05	0.20 to 0.35	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	1600	1550

(a) This grade can be expected to have 0.0005% min boron

Composition Limits of Standard Alloy Steels (February 1954)

AISI No.	C	Mn	P (max)	S (max)	Si	Ni	Cr	Mo	SAE No.
1330	0.28 to 0.33	1.60 to 1.90	0.040	0.040	0.20 to 0.35	.....	.....	.....	1330
1335	0.33 to 0.38	1.60 to 1.90	0.040	0.040	0.20 to 0.35	.....	.....	.....	1335
1340	0.38 to 0.43	1.60 to 1.90	0.040	0.040	0.20 to 0.35	.....	.....	.....	1340
1345	0.43 to 0.48	1.60 to 1.90	0.040	0.040	0.20 to 0.35	.....	.....	.....	1345
2317	0.15 to 0.20	0.40 to 0.60	0.040	0.040	0.20 to 0.35	3.25 to 3.75	.....	.....	2317
2515	0.12 to 0.17	0.40 to 0.60	0.040	0.040	0.20 to 0.35	4.75 to 5.25	.....	.....	2515
E2517	0.15 to 0.20	0.45 to 0.60 ^(a)	0.025	0.025	0.20 to 0.35	4.75 to 5.25	.....	.....	2517
3120	0.17 to 0.22	0.60 to 0.90	0.040	0.040	0.20 to 0.35	1.10 to 1.40	0.55 to 0.75	.....	3120
3130	0.28 to 0.33	0.60 to 0.80	0.040	0.040	0.20 to 0.35	1.10 to 1.40	0.55 to 0.75	.....	3130
3135	0.33 to 0.38	0.60 to 0.80	0.040	0.040	0.20 to 0.35	1.10 to 1.40	0.55 to 0.75	.....	3135
3140	0.38 to 0.43	0.70 to 0.90	0.040	0.040	0.20 to 0.35	1.10 to 1.40	0.55 to 0.75	.....	3140
E3310	0.09 to 0.13	0.45 to 0.60 ^(a)	0.025	0.025	0.20 to 0.35	3.25 to 3.75	1.40 to 1.75	.....	3310
E3316	0.14 to 0.19	0.45 to 0.60 ^(a)	0.025	0.025	0.20 to 0.35	3.25 to 3.75	1.40 to 1.75	.....	3316
4023	0.20 to 0.25	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4023
4024	0.20 to 0.25	0.70 to 0.90	0.040	0.035 to 0.050	0.20 to 0.35	.....	.....	0.20 to 0.30	4024
4027	0.25 to 0.30	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4027
4028	0.25 to 0.30	0.70 to 0.90	0.040	0.035 to 0.050	0.20 to 0.35	.....	.....	0.20 to 0.30	4028
4032	0.30 to 0.35	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4032
4037	0.35 to 0.40	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4037
4042	0.40 to 0.45	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4042
4047	0.45 to 0.50	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4047
4053	0.50 to 0.56	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4053
4063	0.60 to 0.67	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4063
4068	0.63 to 0.70	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	.....	0.20 to 0.30	4068
4118	0.18 to 0.23	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.40 to 0.60	0.08 to 0.15	4118
4130	0.28 to 0.33	0.40 to 0.60	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4130
4135	0.33 to 0.38	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4135
4137	0.35 to 0.40	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4137
4140	0.38 to 0.43	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4140
4142	0.40 to 0.45	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4142
4145	0.43 to 0.48	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4145
4147	0.45 to 0.50	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4147
4150	0.48 to 0.53	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.60 to 1.10	0.15 to 0.25	4150
4320	0.17 to 0.22	0.45 to 0.65	0.040	0.040	0.20 to 0.35	1.65 to 2.00	0.40 to 0.60	0.20 to 0.30	4320
4337	0.35 to 0.40	0.60 to 0.80 ^(b)	0.040	0.040	0.20 to 0.35	1.65 to 2.00	0.70 to 0.90	0.20 to 0.30	4337
4340	0.38 to 0.43	0.60 to 0.80	0.040	0.040	0.20 to 0.35	1.65 to 2.00	0.70 to 0.90	0.20 to 0.30	4340
E4340	0.38 to 0.43	0.65 to 0.85	0.025	0.025	0.20 to 0.35	1.65 to 2.00	0.70 to 0.90	0.20 to 0.30	E4340
4608	0.06 to 0.11	0.25 to 0.45	0.040	0.040	0.25 max	1.40 to 1.75	.....	0.15 to 0.25	4608
4615	0.13 to 0.18	0.45 to 0.65	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	4615
4617	0.15 to 0.20	0.45 to 0.65	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	4617
4620	0.17 to 0.22	0.45 to 0.65	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	4620
X4620	0.18 to 0.23	0.50 to 0.70	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	X4620
4621	0.18 to 0.23	0.70 to 0.90	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	4621
4640	0.38 to 0.43	0.60 to 0.80	0.040	0.040	0.20 to 0.35	1.65 to 2.00	.....	0.20 to 0.30	4640
4812	0.10 to 0.15	0.40 to 0.60	0.040	0.040	0.20 to 0.35	3.25 to 3.75	.....	0.20 to 0.30	4812
4815	0.13 to 0.18	0.40 to 0.60	0.040	0.040	0.20 to 0.35	3.25 to 3.75	.....	0.20 to 0.30	4815
4817	0.15 to 0.20	0.40 to 0.60	0.040	0.040	0.20 to 0.35	3.25 to 3.75	.....	0.20 to 0.30	4817
4820	0.19 to 0.23	0.50 to 0.70	0.040	0.040	0.20 to 0.35	3.25 to 3.75	.....	0.20 to 0.30	4820
5015	0.12 to 0.17	0.30 to 0.50	0.040	0.040	0.20 to 0.35	.....	0.30 to 0.50	.....	5015
5046	0.43 to 0.50	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.20 to 0.35	.....	5046
5117	0.15 to 0.20	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5117
5120	0.17 to 0.22	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5120
5130	0.28 to 0.33	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.80 to 1.10	.....	5130
5132	0.30 to 0.35	0.60 to 0.80	0.040	0.040	0.20 to 0.35	.....	0.75 to 1.00	.....	5132
5135	0.33 to 0.38	0.60 to 0.80	0.040	0.040	0.20 to 0.35	.....	0.80 to 1.05	.....	5135
5140	0.38 to 0.43	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5140
5145	0.43 to 0.48	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5145
5147	0.45 to 0.52	0.70 to 0.95	0.040	0.040	0.20 to 0.35	.....	0.85 to 1.15	.....	5147
5150	0.48 to 0.53	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5150
5152	0.48 to 0.55	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.90 to 1.20	.....	5152
5155	0.50 to 0.60	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5155
5160	0.55 to 0.65	0.75 to 1.00	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	.....	5160
E50100	0.95 to 1.10	0.25 to 0.45	0.025	0.025	0.20 to 0.35	.....	0.40 to 0.60	.....	50100
E5100	0.95 to 1.10	0.25 to 0.45	0.025	0.025	0.20 to 0.35	.....	0.90 to 1.15	.....	51000
E52100	0.95 to 1.10	0.25 to 0.45	0.025	0.025	0.20 to 0.35	.....	1.30 to 1.60	.....	52100
6117	0.15 to 0.20	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	0.10 min V	6117
6120	0.17 to 0.22	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.70 to 0.90	0.10 min V	6120
6145	0.43 to 0.48	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.80 to 1.10	0.15 min V	6145
6150	0.48 to 0.53	0.70 to 0.90	0.040	0.040	0.20 to 0.35	.....	0.80 to 1.10	0.15 min V	6150
6165	0.13 to 0.18	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6165
6167	0.15 to 0.20	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6167
6200	0.18 to 0.23	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6200
6222	0.20 to 0.25	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6222
6225	0.23 to 0.28	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6225
6227	0.25 to 0.30	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6227
6330	0.28 to 0.33	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6330
6335	0.33 to 0.38	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.50 to 0.80	0.15 to 0.25	6335
6337	0.35 to 0.40	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6337
6640	0.39 to 0.43	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6640
6641	0.39 to 0.43	0.75 to 1.00	0.040	0.040 to 0.060	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6641
6642	0.40 to 0.45	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6642
6645	0.43 to 0.48	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6645
6650	0.48 to 0.53	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6650
6653	0.50 to 0.56	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.50 to 0.80	0.15 to 0.25	6653
6655	0.50 to 0.60	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6655
6660	0.55 to 0.65	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6660
6645 ^(b)	0.43 to 0.48	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.15 to 0.25	6645
8715	0.13 to 0.18	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8715
8717	0.15 to 0.20	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8717
8720	0.18 to 0.23	0.70 to 0.90	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8720
8735	0.33 to 0.38	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8735
8740	0.38 to 0.43	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8740
8742	0.40 to 0.45	0.75 to 1.00	0.040	0.040	0.20 to 0.35	0.40 to 0.70	0.40 to 0.60	0.20 to 0.30	8742
8750	0.48 to 0.53	0.75 to 1.00	0.040	0.040	0.20 to 0.35</				

The Selection of Tool Steels

By the ASM Committee on Tool Steel

IN THE 1948 ASM Metals Handbook, a brief discussion is given (pages 658 and 659) of the principal characteristics of tool steels that determine their selection for particular uses.

The article presented here supplements the 1948 discussion of selection in the following ways:

- 1 A classification of tool steels different from the one on page 656 of the 1948 Handbook is defined and employed.
- 2 Basic factors in selection are further clarified so as to enhance the value of the table on page 659 of the 1948 Handbook.
- 3 Detailed consideration is given to the selection of tool steels for each of 17 important types of tools, and specific grades are recommended for each type.

Principal Types of Tool Steels

The tool steels considered here are classified both by the method introduced in the 1948 ASM Metals Handbook and that more recently adopted by AISI and SAE. Table I is a cross-index arranged in the numerical order of the 1948 ASM designations. Table II shows the complete list of steels in terms of the AISI-SAE classification. Throughout the text that follows, AISI-SAE designations are used exclusively wherever possible.

As shown in Table I, the AISI-SAE method identifies each steel by a letter and a number. The letter places the steel in a recognizable group or class of steels; the number distinguishes one steel from another within each group. Most of the groups are similar to those employed in the principal table on page 656 of the 1948 Handbook.

Factors in Selection

Correlation of the metallurgical characteristics of tool steels with the requirements of the tool in operation is the only sound approach to tool steel selection. It should be emphasized that the choice of a tool steel is usually not limited to a single type or even to a particular group. Many tool steels will perform on any given job, and the tool life obtained with each of them must be judged by weighing such factors as expected productivity, ease of fabrication, and cost. Final cost per unit part produced by the tool is the ultimate basis of proper selection.

The following characteristics of tool steel, listed in the order tabulated on pages 658 and 659 of the 1948 Handbook, are the most important in selection: "nondeforming" properties, safety in hardening, toughness, resistance to the softening effect of heat, wear resistance, machinability, the quenching medium required, hardening temperature range, depth of hardening, and resistance to decarburization.

The first step in selection is to establish which of these characteristics are most important for the problem at hand. One may logically begin by asking these questions about a given application: Does the tool cut? Shear? Form? Draw? Extrude? Roll? Batter? Is the work performed hot or cold? Is the anticipated load on the tool light

or heavy? Is the load intermittent and light, or intermittent with heavy shock? Is the load continuous? Is the design of the tool a factor in determining the required edge strength? Is the cutting portion of the tool well supported? Does it have an acute angle and therefore a fine, thin edge? Is there apt to be vibration within the tool or in the holding mechanism? What abrasive

cost per unit part produced by the tool—the ultimate aim of selection.

Another factor, not encountered in the above discussion or in Table IV, is availability: Certain grades of tool steel cannot be delivered as promptly as others because of low production of those grades. There are about twelve grades of tool steel that can be found in stock in almost every warehousing district and that are made by the majority of tool steel producers. These grades, which are in the greatest demand for tool and die work, are as follows:

- W1—Carbon tool steel with approximately 1% C
W2—Carbon-vanadium steel with approximately 0.90% C
O1—Manganese oil-hardening "non-deforming" die steel
A2—5% Cr air-hardening die steel

Table I. Cross-Index of Tool Steel Designations

ASM (1948)	AISI-SAE
Carbon Tool Steels	
IA	W1★
IB	W4, W5
IC	W2★, W3
"Nondeforming" Tool Steels	
IIA1	O1★
IIA2	O2
IIA3	O7
IIB1	A4, A5, A6
IIB2	A2★
IIC1	D3★, D6
IID1	D1
IID2	D2★, D5
IID3	D4★
Shock-Resisting Tool Steels	
III A	J2
III B	S2
III C	S4★, S5★
III D	S1★
III E	S1★
Hot Work Tool Steels	
IV A1	
IV A2	
IV B	H11★, H12★, H13
IV C	H14
IV D	H16
IV E1	H15
IV E2	
IV F1	H20★, H21★
IV F2	H22
IV F3	H24, H25
IV F4	H26
High Speed Tool Steels	
V A1	M10
V A2	M1
V A3	M2★
V A4	M4
V B1	M30
V B2	M34
V B3	M35
V B4	M36
V C1	T1★
V C2	T2
V C3	T3
V D1	T8
V D2	T4
V D3	T5
V D4	T6
Miscellaneous Tool Steels	
VIA	P1
VIB	P3
VIC	
VID	
VIE	L6
VIF1	L6
VIF2	
VIF3	
VIG	
VIH	
VII	
VIJ	L3
VIK	F2, F3

Supplements the Tool Steels section of the 1948 ASM Metals Handbook, pages 653 to 676

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

Table II. Classification and Approximate Compositions of Principal Types of Tool Steels

AISI-SAE	ASM (1948)	C	Mn	Si or Ni	Cr	V	W	Mo	Co
Water-Hardening Tool Steels^(a)									
W1★	IA	0.60-1.40 ^(a)	....	....	....	0.25	....	....	....
W2★	IC	0.60-1.40 ^(a)	....	....	....	0.50	....	....	....
W3	IC	0.60-1.40 ^(a)	....	....	....	0.50	....	....	....
W4	IB	0.60-1.40 ^(a)	....	....	0.25	....	....	....	....
W5	IB	0.60-1.40 ^(a)	....	....	0.50	....	....	....	....
W6	....	0.60-1.40 ^(a)	....	....	0.25	0.25	....	....	....
W7	....	0.60-1.40 ^(a)	....	....	0.50	0.20	....	....	....
Shock-Resisting Tool Steels									
S1★	III D & E	0.50	....	1.00 Si	1.50	....	2.50	....	....
S2	III B	0.50	....	1.00 Si	0.75	....	1.00	0.50	....
S3	....	0.50	....	2.00 Si	0.75	....	....	....	....
S4★	III C	0.50	0.80	2.00 Si	....	....	....	....	....
S5★	III C	0.50	0.80	2.00 Si	....	....	....	0.40	....
Oil-Hardening Cold Work Tool Steels									
O1★	II A1	0.90	1.00	....	0.50	....	0.50	....	....
O2	II A2	0.90	1.60	....	....	....	....	....	....
O6	....	1.45	0.75	1.00 Si	....	....	....	0.25	....
O7	II A3	1.20	....	....	0.75	....	1.75	0.25 (optional)	....
Air-Hardening Medium-Alloy Cold Work Tool Steels									
A2★	II B2	1.00	....	....	5.00	....	....	1.00	....
A4	II B1	1.00	2.00	....	1.00	....	....	1.00	....
A5	II B1	1.00	3.00	....	1.00	....	....	1.00	....
A6	II B1	0.70	2.00	....	1.00	....	....	1.00	....
High-Carbon High-Chromium Cold Work Steels									
D1	II D1	1.00	....	....	12.00	....	....	1.00	....
D2★	II D2	1.50	....	....	12.00	....	....	1.00	....
D3★	II C1	2.25	....	....	12.00	....	....	....	....
D4★	II D3	2.25	....	....	12.00	....	....	1.00	....
D5	II D2	1.50	....	....	12.00	....	....	1.00	3.00
D6	II C1	2.25	....	1.00 Si	12.00	....	1.00	....	....
Chromium Hot Work Tool Steels									
H11★	IV B	0.35	....	....	5.00	0.40	....	1.50	....
H12★	IV B	0.35	....	....	5.00	0.40	1.50	1.50	....
H13	IV B	0.35	....	....	5.00	1.00	....	1.50	....
H14	IV C	0.40	....	....	5.00	....	5.00	....	....
H15	IV E1	0.40	....	....	5.00	....	....	5.00	....
H16	IV D	0.55	....	....	7.00	....	7.00	....	....
Tungsten Hot Work Tool Steels									
H20★	IV F1	0.35	....	....	2.00	....	9.00	....	....
H21★	IV F1	0.35	....	....	3.50	....	9.00	....	....
H22	IV F2	0.35	....	....	2.00	....	11.00	....	....
H23	....	0.30	....	....	12.00	....	12.00	....	....
H24	IV F3	0.45	....	....	3.00	....	15.00	....	....
H25	IV F3	0.25	....	....	4.00	....	15.00	....	....
H26	IV F4	0.50	....	....	4.00	1.00	18.00	....	....
Molybdenum Hot Work Tool Steels									
H41	....	0.65	....	....	4.00	1.00	1.50	8.00	....
H42	....	0.60	....	....	4.00	2.00	6.00	5.00	....
H43	....	0.55	....	....	4.00	2.00	....	8.00	....
Tungsten High Speed Tool Steels									
T1★	VC1	0.70	....	....	4.00	1.00	18.00	....	....
T2	VC2	0.85	....	....	4.00	2.00	18.00	....	....
T3	VC3	1.00	....	....	4.00	3.00	18.00	....	....
T4	VD2	0.75	....	....	4.00	1.00	18.00	....	5.00
T5	VD3	0.80	....	....	4.00	2.00	18.00	....	8.00
T6	VD4	0.80	....	....	4.50	1.50	20.00	....	12.00
T7	....	0.80	....	....	4.00	2.00	14.00	....	....
T8	VD1	0.80	....	....	4.00	2.00	14.00	....	5.00
T9	....	1.20	....	....	4.00	4.00	18.00	....	....
T15	....	1.55	....	....	4.00	5.00	12.00	....	5.00
Molybdenum High Speed Tool Steels									
M1	VA2	0.80	....	....	4.00	1.00	1.50	8.00	....
M2★	VA3	0.85	....	....	4.00	2.00	6.00	5.00	....
M3	....	1.00	....	....	4.00	2.75	6.00	5.00	....
M4	VA4	1.30	....	....	4.00	4.00	5.50	4.50	....
M6	....	0.80	....	....	4.00	1.50	4.00	5.00	12.00 Cb
M8	....	0.80	....	....	4.00	1.50	5.00	5.00	12.00 Cb
M10	VA1	0.85	....	....	4.00	2.00	....	8.00	....
M30	VB1	0.85	....	....	4.00	1.25	2.00	8.00	5.00
M34	VB2	0.85	....	....	4.00	2.00	2.00	8.00	8.00
M35	VB3	0.85	....	....	4.00	2.00	6.00	5.00	5.00
M36	VB4	0.85	....	....	4.00	2.00	6.00	5.00	8.00
Low-Alloy Special-Purpose Tool Steels									
L1	....	1.00	....	....	1.25	....	....	....	....
L2	III A	0.50-1.10 ^(a)	....	....	1.00	0.20	....	....	....
L3	VI J	1.00	....	....	1.50	0.20	....	....	....
L4	....	1.00	0.60	....	1.50	0.20	....	....	....
L5	....	1.00	1.00	....	1.00	....	....	0.25	....
L6	VIF1 & E	0.70	....	1.50 Ni	0.75	....	....	0.25 (optional)	....
L7	....	1.00	0.35	....	1.40	....	....	0.40	....
Carbon-Tungsten Tool Steels									
F1	....	1.00	....	....	....	....	1.25	....	....
F2	VI K	1.25	....	....	....	....	3.50	....	....
F3	VI K	1.25	....	....	0.75	....	3.50	....	....
Low-Carbon Mold Steels									
P1	VIA	0.10 max.	....	0.50 Ni	1.25	....	....	0.20	....
P2	....	0.07 max.	....	1.25 Ni	0.60	....	....	....	....
P3	VI B	0.10 max.	....	....	5.00	....	....	....	....
P4	....	0.07 max.	....	....	2.25	....	....	....	....
P5	....	0.10 max.	....	....	0.75	....	....	0.25	....
P20	....	0.30	....	....	0.75	....	....	....	....
Other Steels Listed in 1948 Metals Handbook and Not Included Above									
....	IV A1	0.65	....	....	4.00	0.75	....	0.50	....
....	IV A2	0.90	....	....	4.00	0.75 (optional)	0.50 (optional)	....	....
....	VIC	0.12	....	3.50 Ni	1.50	....	....	....	....
....	VID	0.35	....	....	12.00	....	....	....	....
....	VIF2	0.50	....	1.60 Ni	1.00	0.10 (optional)	0.30	....	....
....	VIF3	0.55	....	2.00 Ni	1.00	0.10 (optional)	0.75	....	....
....	VIG	0.55	....	....	1.00	0.10	....	0.45	....
....	VI H	1.25	0.60	....	0.50	....	....	....	....
....	VII	1.25	0.85	....	0.50	....	....	0.50	....

D2—Air-hardening high-carbon high-chromium die steel with 1.5% C and 12% Cr

D4 or D3—Air-hardening or oil-hardening high-carbon high-chromium die steel with approximately 2.2% C and 12% Cr

T1—18-4-1 tungsten high speed steel

M2—6-5-4-2 tungsten-molybdenum high speed steel

H11 or H12—5% Cr hot work die steel

H20 or H21—9% W hot work die steel

S1—Tungsten chisel steel

S4 or S5—Silicon-manganese oil-hardening or water-hardening tool steel.

Where a double choice is indicated above it means that the two steels are nearly interchangeable, and final selection depends on minor factors of the individual job.

Example. As an example of the selection procedure and as a guide in using the accompanying information, let us consider the selection of tool steel for a die for blanking and forming of low-carbon sheet stock $\frac{1}{16}$ in. thick. First, it is recognized that two principal operations are involved: shearing (the blanking operation) and forming. Table III indicates that wear resistance and toughness are the major factors, with safety in hardening and freedom from distortion in hardening also of importance. It is determined that this work will be done cold, that is, at room temperature, and immediately the hot work steels designated by the letter H can be eliminated from consideration.

It should next be determined whether the die can be machined to size prior to heat treatment and then put to use, or whether the tolerances of the finished part are such that the die must be ground after heat treatment. If it can be machined to size prior to heat treatment, then it is important to select a steel having good resistance to decarburization and subject to only slight dimensional change during heat treatment. If it must be ground all over after heat treatment, then these two factors become of less importance, unless, of course, the cost of grinding itself is prohibitive because of the high wear resistance of the steel selected, or the design of the tool.

If the die is to be ground on all dimensions after heat treatment, then an oil-hardening steel from group O would probably be chosen. Since these steels have fair wear resistance and good resistance to decarburization, it would not be anticipated that such a steel would give difficulty in grinding. However, the length of run may be quite large—several hundred thousand or more—making wear resistance even more important. Steels A and D, T and M have good wear resistance but steels T and M are of high cost, require high hardening temperatures and may not be considered except in special instances. Group D steels have considerably better wear resistance than group A, and although they are both air-hardening and permit only slight distortion, steels in group D would be expected to give longer life.

Thus, by this process of deduction, it is decided that a high-carbon high-chromium steel will be employed. Selection within the group of six high-carbon high-chromium steels is largely

★Stocked in almost every warehousing district and made by the majority of tool steel producers.

(a) Various carbon contents are available in 0.10% ranges.

Tool Steel Selection

a matter of deciding which carbon content is desired, and whether or not air-hardening characteristics are wanted. As a compromise of toughness and wear resistance, the air-hardening steel D2, with 1.5% C, would be a good selection.

Deductive reasoning similar to the example just given (and sometimes more involved) underlies the selections indicated more briefly for the 17 classes of tools discussed below.

Cutting Tools

The cutting tools considered here are those normally used under machine power to cut metal pieces to size and shape by removing chips—that is, taps, dies, reamers, milling cutters, drills, broaches, hobs and lathe tools.

There can be no simple and definite system of rules for the selection of material for cutting tools. Certain factors may predominate in one application whereas in another an entirely different set of considerations may be involved. For example, consider a flat form-tool of rather complicated shape and section size. If one such tool were needed quickly to make only a small quantity of parts and possibly not be used again, it might be made of any grade of oil-hardening alloy tool steel readily available. But if the tool were to be used in an automatic machine for continuous high-speed repetitive production, it should be made of high speed steel or tipped with sintered carbide.

Most steel cutting tools are made from one of the following classes:

- 1 Water-hardening carbon or low-alloy tool steels (Groups W and F)
- 2 Oil-hardening low-alloy or medium-alloy tool steels (Groups O and L)
- 3 High speed steels (Groups T and M)

Water-Hardening Steels. Tools such as taps, tapper taps, thread-cutting dies, drills, reamers and chasers, which are symmetrical in shape and do not require a high degree of red hardness in service, are frequently made of carbon tool steel (group W). If extreme wear resistance at the expense of some toughness and ease of manufacturing is desired, the tungsten finishing steels of group F may be used in this class.

Advantages. The water-hardening steels are shallow hardening; in sections of about $\frac{1}{2}$ in. and larger, they will develop a hard case and a softer tough core. This combination contributes to higher over-all toughness than is found in through-hardening steels. Water-hardening steels are

lower in price and more easily machined than most of the higher-alloy steels. Heat treatment is easily performed in the simplest types of furnace equipment. Finished tools have good edge strength and wear resistance, if not heated above about 350°F in service.

Disadvantages. Water-hardening steels are the most susceptible to crack-

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ing or distortion during hardening and should not be used for complicated or unbalanced designs or where holes, slots, keyways or sharp corners are necessary to the proper functioning of the tool. Tools made of these steels will soften and lose their cutting edges rapidly if heated excessively in service. Similarly, extreme care must be taken when grinding the cutting edges, either in original manufacture or in subsequent sharpening, lest softening or sur-

face cracking occur. (The threaded tools mentioned above are generally not ground in the angle of the threads when made of water-hardening steels.)

The water-hardening steels do not permit any form of surface treatment such as nitriding or oxidizing after the tool is in the finished condition because of the softening effect of these treatments on the base metal. Simple dimensional changes (not distortion or cracking) are hard to predict or allow for in hardening these steels because of the varying percentages of case and core developed in different sizes and shapes—some tools will shrink and some will expand during hardening.

Choice of Grade. The selection of one grade from the ten included in these two groups is usually based on availability, familiarity through past experience, toughness, wear resistance, grindability, hardenability, and to some extent the cost of steel (not necessarily in the order listed). Steel W1★ can be obtained in a variety of carbon contents (sometimes called "temper") ranging from about 0.80 to 1.20%. Wear resistance is directly proportional to carbon content and toughness is inversely proportional. Although some variation in depth of hardening can be obtained, this is essentially a shallow-hardening steel.

If slightly greater hardenability is desired, as for example in large tools with heavy sections, the grades containing chromium (W4, W5, W6, W7) should be considered. The carbon-vanadium steels (W2★ and W3) are noted for their ability to remain fine-grained when slightly overheated in hardening. Therefore, they should be used when there is a lack of good control of the heat treating process, or when tools have widely varying sections that might coarsen in hardening.

The tungsten finishing steels of group F are characterized by their unique ability to maintain a sharp cutting edge under conditions of high abrasiveness but relatively light loads and low speeds. They do not have true red hardness and should not be confused with high speed steel. These F steels are very difficult to grind and should be used only when extra cost in grinding is justified in order to obtain a keener, longer lived finishing tool than can be produced from one of the W steels. Grade F1 is the easiest to grind and also the least abrasion-resistant. Because of its chromium content, F3 is the deepest-hardenning and therefore most suitable for large tools.

Oil-Hardening Low-Alloy and Medium-Alloy Tool Steels. These steels of groups O and L find very limited use in cutting tools of the types included here. They may, however, be used occasionally for taps with square or special thread forms, solid threading dies, form tools, expansion reamers or taps, or any special design of tool having sharp angles, thin projections, holes, slots, notches, or recesses, where safety in hardening is required and economic factors do not justify the use of high speed steel.

Advantages. The principal feature of oil-hardening steels in the manufacture of cutting tools is their "non-deforming" characteristic; predictabil-

★Stocked in almost every warehousing district and made by the majority of tool steel producers.

Table III. First Step Toward Selection

If the Tool	These Major Characteristics Are Required in the Tool Steel	And These Minor Characteristics May Be Required
Cuts	Wear resistance and resistance to softening effect of heat	Grindability and toughness
Shears	Wear resistance and toughness	Safety in hardening and slight distortion in hardening
Forms	Wear resistance	Machinability and toughness
Draws	Wear resistance	Slight distortion in hardening
Extrudes	Resistance to softening effect of heat, toughness and wear resistance	*****
Rolls	Wear resistance	*****
Batters	Toughness	Wear resistance

Table IV. Comparison of Principal Groups of Tool Steels

AISI-SAE	Steel Group ^(a) ASM (1948)	Cost of Steel	Toughness	Maximum Recommended Hardness, ^(b) Rockwell C	Resistance to Softening Effect of Heat	Wear Resistance	Machinability
W	I	Low	Low-High	60-67	Low	Low-High	Good
O	IIA	Low	Medium	60-64	Low	Medium	Good
A	IIIB	Low	Medium	60-64	Medium	High	Fair
D	IIIC, IID	Medium	Low	60-64	Medium	High	Poor
H	IV	Low-High	High	40-56	High	Medium	Fair
T	VC, VD	High	Low	Over 64	High	High	Fair
M	VA, VB	High	Low	Over 64	High	High	Fair
S	III	Low	High	56-60	Medium	Low	Good
AISI-SAE	Steel Group ^(c) ASM (1948)	Distortion in Hardening	Safety in Hardening	Quenching Mediums	Hardening Temperature Range, ^(d) deg Fahr	Depth of Hardening	Tendency Toward Decarburization
W	I	High	Low-Med	Water	1400 to 1600	Shallow	Low
O	IIA	Medium	Medium	Oil	1400 to 1600	Medium	Low
A	IIIB	Low	High	Air	1450 to 1850	Deep	Medium
D	IIIC, IID	Low	High	Air, Oil	1700 to 2000	Deep	Medium
H	IV	Low	High	Air, Oil	1700 to 2250	Deep	Medium
T	VC, VD	Low-High	High	Oil, Air, Salt	2150 to 2400	Deep	Medium
M	VA, VB	Low	High	Oil, Air, Salt	2125 to 2275	Deep	High
S	III	Med-High	Low-Med	Water, Oil	1550 to 1800	Medium	High

(a) Steels in groups F, P and L are omitted from this table because they represent specialized applications.

(b) Different steels within the group have different maximums within the range of hardness shown.

(c) The purpose of this column is to show the broad ranges of

temperature employed in hardening. This information may serve to indicate the heat treating equipment required; it is not to be used as a specification. For more exact information, see the articles on heat treatment of tool steels, pages 660 to 676 of the 1948 Metals Handbook.

ity of the amount of volume change in hardening makes them important where accurate control of size change is essential. Also, they are much less likely to bend, sag, twist, distort or crack during heat treatment than are the water-hardening steels. They are lower in price and somewhat easier to machine than the high speed steels and do not require special high-temperature furnace equipment.

Disadvantages. The oil-hardening steels are not quite equal to water-hardening steels in ability to develop and maintain a keen cutting edge for fine finishes, their abrasion resistance is certainly no better than carbon tool steel, and they have no greater red hardness. The initial cost is higher than for carbon steels, and they are not suitable for final surface treatments. Their toughness is usually relatively low and they are not easy to grind without cracking or softening.

Choice of Grade. Although there are some metallurgical differences among these eleven steels with respect to processing and finished properties, there is a great deal of overlapping, and final selection is based to a large extent on availability, past experience and price. Grades O1★ and O2 are popular as general-purpose steels. However, many of the chromium-bearing steels such as O7, L1, L2, L3, L4 and L7 will produce tools with about the same qualities. Within these grades, those containing molybdenum have greater hardenability. Steel L6 with its content of nickel and low carbon is particularly suitable for tools requiring extreme toughness and shock resistance at the expense of high hardness and wear resistance.

High Speed Tool Steels. Under present-day conditions of large-volume repetitive production of parts made from all types of material, including heat treated steels and highly alloyed stainless and heat-resisting materials, by far the majority of tool steel cutting tools of the types covered in this section are made of some grade of high speed steel (groups T and M).

Advantages. The outstanding characteristic of high speed steels, as their name implies, is the ability to operate successfully at speeds and other cutting conditions which cause the cutting edge of the tool to attain a high temperature of 1000 to 1100°F while cutting. At this temperature these steels are still hard enough to cut metal and on cooling to room temperature they will regain their original cold hardness. This property is called "red hardness" and is the outstanding property of high speed steel. Furthermore, because of the high content of alloy carbides, these steels exhibit wear resistance superior to water-hardening or oil-hardening tool steels, even though the temperature of the latter in service remains at or only slightly above room temperature. For this reason cutting tools made of high speed steel will last longer than water-hardening or oil-hardening steel tools.

The high speed steels are relatively easy to harden when suitable heat treating equipment is available. Since they can be fully hardened throughout the entire cross section of ordinary cutting tools by quenching in oil or molten salt baths, or even by air cooling, the tendency to crack or distort during heat treating is slight, providing the tools are properly handled and supported while at the elevated temperatures required for hardening. Thus, tools of complicated and irregular shape which should not be made of water-hardening steel can be made of high speed steel with comparative safety. Because of their red hardness, the general-purpose grades are less susceptible to softening or cracking in grinding than are the water-hardening or oil-hardening steels. And lastly, because of their ability to resist softening on reheating after hardening, the high speed steels lend themselves to a variety of auxiliary surface hardening or oxidizing treatments in the finished or semi-finished condition.

Disadvantages. The principal disadvantages of high speed steel are economic. The initial cost is high, ma-

chining is relatively costly, the special high-temperature furnace equipment required for heat treating is expensive to install and to maintain, and the longer time required for a complete hardening and tempering cycle increases production costs.

Some of the more highly alloyed abrasion-resistant grades present difficulty in grinding threads or other complex shapes, resulting in added expense. In addition, while the toughness or shock resistance of properly hardened and tempered high speed steel is adequate for most cutting applications, there are certain jobs involving twisting, bending, shock or unavoidable misalignment where the superior toughness of carbon tool steel that has been hardened with a hard case and soft core is advantageous.

Despite the economic disadvantages just enumerated, once a cutting tool has been properly made of high speed steel, it is most likely to be a better performing, more accurate and longer lived tool than can be made from any other type of steel and, therefore, may easily justify the added cost of manufacturing. Also, for those applications where high temperature is generated at the cutting edge, high speed steel is the *only* type of steel which can be considered, regardless of cost.

Choice of Grade. Among the 21 grades of high speed steel listed, there is considerable range of choice for most applications. The final selection should be based on a discreet balance of the economic factors of steel cost, ease of manufacture, and availability, against the metallurgical requirements of the finished tool (principally red hardness, abrasion resistance and toughness).

By far the majority of tools for ordinary applications should be made from one of the four grades of general-purpose high speed steel, T1★, M1, M2★ and M10. During 1953, more than 90% of the total high speed steel ship-

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

Table V. Recommended Sizes and Applications of Pretreated Die Blocks in the Usual Hardness Ranges

Sclero-scope	Hardness Brinell	Cross Section, in.	Length, in.	Weight, lb	Recommended Applications
55 to 60	380 to 420	10 by 17	20	1000	Dies having shallow impressions (up to $\frac{3}{4}$ in. deep) such as for small tools, wrenches, pliers, gear blanks, small connecting rods, track links
50 to 55	340 to 380	15 by 20	36	3250	General forgings not containing deep locks or intricate designs with medium impressions (up to 2 in. deep) such as connecting rods, knuckles, small axles, rims and gears
45 to 50	300 to 340	15 by 28	48	6000	Large parts with impressions up to 5 in. deep. The greater toughness at this hardness level permits more intricate designs and deeper locks such as large connecting rods, axles, aircraft landing gears, propeller hubs and turbine wheels
40 to 45	270 to 300	Size limited only by facilities of vendor			Impressions extremely large or of intricate design such as large crankshafts, connecting rods, crankcase housings, landing gear columns and wing spar sections

ments were of these four types, distributed as follows:

M2★	46.0%
M1	21.5
M10	14.9
T1★	9.5
All others	8.1
	100.0%

Although having some minor differences that can best be evaluated by experience, these four grades are closely similar in performance. They are the lowest priced grades, are most readily available from stock and, neglecting variations in heat treatment, are the toughest of the high speed steels. They represent a logical starting point in selection from which one may progress either toward increased red hardness or greater wear resistance or both.

When greater-than-average red hardness is needed, the steels containing cobalt are recommended. When the material being cut is highly abrasive and dulls ordinary tools rapidly, the steels containing higher contents of vanadium are the logical choice. In steel T15 a combination of cobalt plus high vanadium provides superiority in both red hardness and abrasion resistance. All of these highly alloyed grades are invaluable in meeting the current demand for super high speed steel cutting tools. However, their use is subject to limitations: The high-cobalt steels require better-than-average protection against decarburization during heat treatment, especially if all working surfaces are not to be ground after hardening. Also, these steels are more brittle and must be protected against excessive shock or vibration in service. The high-vanadium steels are more difficult to grind; both the tool manufacturer and the tool user must have satisfactory grinding wheels and machines so as not to nullify, by too-expensive grinding and sharpening, the benefits to be gained through the longer life of the tools.

Molybdenum Versus Tungsten. From the standpoint of fabrication and tool performance, there is little difference between the molybdenum and tungsten grades. Each group has many proponents but extensive laboratory studies and many carefully conducted production comparisons have failed to establish any consistent outstanding superiority for comparable grades of the two groups. The important properties of red hardness, abrasion resistance and toughness are about the same. Response to heat treatment, machinability and grindability in grades of equal vanadium and cobalt contents

are practically identical. It is difficult to establish any technical reason for recommending grades from one group over comparable grades from the other.

Of course, all of the grades are not comparable. There are certain special-purpose steels in each group, such as T6, T7, T8, T15 and M6, M8, M35 and M36, which have no close counterparts in the other group. The unique compositions, properties or prices of these steels suited them especially well for certain uses without competition from any grade in the opposite group.

Since there are adequate sources of molybdenum in the United States to supply domestic requirements, whereas most of the tungsten must be imported, and since the molybdenum steels are lower in price than the tungsten steels, increased use of molybdenum steels is logical. Changes in the consumption of molybdenum grades during the last five years are plotted in Fig. 1, which shows that between 80 and 90% of all the high speed steel produced is of the molybdenum type.

Die Blocks and Die Inserts

Selection of the proper forging die steel for a given application depends primarily on the following interrelated service considerations: the amount of production required, cost of steel, machining sequence (that is, whether the die impressions are machined before or after the block is hardened), operating temperatures, and shock loading (that is, whether the die is to be used in a forging press or a drop hammer). As the desired properties are frequently not compatible with one another, some compromise is necessary in making the selection.

The three principal causes of pre-

mature die failure are pressure, temperature and abrasive action. Excessive pressure is the least of forging die problems. Dies are usually of ample size and shape, and the effects of pressure can be controlled by vents, reliefs, sprues and lubrication.

Abrasive action is inherent in forging and there is no practical way to prevent it; however, it can be minimized by proper design. Also, the forging operator can do much to minimize abrasive wear by conscientiously removing scale from the die impressions, and the heater can help by avoiding excessive oxygen in the flame, so that minimum scale is formed on the stock to be forged.

Temperature is the largest single cause of early die wear and the effect of heat is a major consideration in selecting a die steel.

Water-Hardening Low-Alloy Die Steels W2★, W3, W4, W5

are used in low-production operations. The resistance of these steels to abrasion at higher temperatures is rather low; they are shallow hardening and subject to distortion when hardened in irregular sections. However, the steels are inexpensive, readily machinable and attain high hardness.

The higher surface hardness of the impression, together with the softer core, warrants their use where thin parts of small section are to be forged to high dimensional accuracy.

Oil-Hardening Low-Alloy Die Steels VIG, VIF2 and VIF3

have greater hardenability and distort less during hardening than the water-hardening steels. The alloy content insures deep and uniform hardening, usually through the entire section; thus the worn impression can be resunk several times without further heat treatment. These steels are low in cost for extended runs, easy to machine and heat treat, and have good resistance to wear and shock at moderate temperatures.

With the availability of prehardened and tempered blocks, machinable at 60 scleroscope (420 Brinell), the use of annealed die blocks has all but vanished. The latter are generally used where greater hardness is needed than is available in the commercially pretreated blocks.

The general-purpose die blocks are supplied commercially in the quenched and tempered condition at four hardness levels as indicated in Table V, showing recommended block sizes and applications.

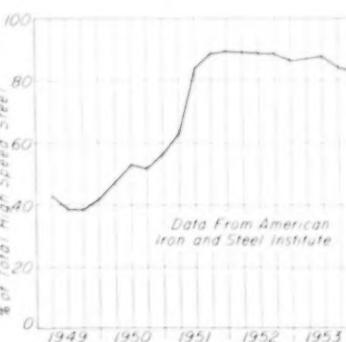


Fig. 1. Trend in Relative Volume of Molybdenum High Speed Steel

Oil-Hardening or Air-Hardening Medium-Alloy Die Steels

H11★, H12★, H13, VIF5

offer improved die life through improved abrasion resistance at temperatures obtained by heat treatment after impressions are sunk. They also have maximum hardenability with minimum distortion and size change. Use of these steels permits the manufacture of more complex and precise dies without added expense for excessive rework or finishing after heat treatment.

Oil-Hardening or Air-Hardening High-Alloy Die Steels

S1★, H20★, H21
H22, H24, H25

have excellent abrasion resistance at high working temperatures, though not without sacrifice of some other properties.

As a group, these steels should outwear the other types of die steels. Usually they are less shock resistant than others, and extreme care must be taken to insure proper mating and alignment, lest early failure occur by chipping, cracking or total failure. Generally these steels are used as hot die inserts in presses and are installed in insert holders made of a low-alloy die steel having good toughness and shock resistance. These complex high-alloy steels offer maximum output where long production runs are anticipated and have high resistance to the softening effects of heat, although machinability must be sacrificed and added care must be taken to heat treat them to best advantage.

Heat Treatments are given on page 666 of the 1948 Metals Handbook.

Tools for Forging Machines

Nearly all of the hot work steels and several of the shock-resisting steels can be used for tools in hot forging machines.

Gripper Dies and Header Dies, for use where surface temperatures do not exceed 800 F and where the forces are largely compressive, are now made primarily from H12★ (0.50% C) or A2★. However, dies having sharp internal corners are likely to break if made from A2. Steel IV-A2 is useful for gripper dies subject to high compression and sliding pressures.

Where high toughness is necessary and wear resistance may be sacrificed, S1★ may be used. For high toughness, good red hardness up to 900 F, and best resistance to heat checking the similar types H11★, H12★, or H13 may be used. For high working temperatures where the surface of the die may have to operate up to 1100 F, H14, H20★, H21★ or H22 may be used, but water cooling of such dies in service is not recommended.

If the working temperatures are above 1100 F, H24, H25 or H26 might be necessary. The toughness of these steels is lower than H14, H20, H21 and H22, and sudden temperature changes must be avoided. Preheating for service must be done carefully and sudden cooling avoided. The cost of steels H24, H25 and H26 is high and their use can be justified only for continuous high production. The hardness of gripper, heading, upsetting or bending dies should be in the range of Rockwell C 45 to 50.

Piercers and Punches subject to severe bending forces and high working temperatures must be made of steels with high toughness, red hardness, resistance to heat checking and resistance to "washing", the properties being listed in order of importance. The need for high red hardness rules out use of the shock-resisting steels. For applications needing moderate red hardness, the H11★, H12★ or H13 steels may be used at Rockwell C 43 to 48; toughness will be excellent. For higher-temperature operations H16, H20★, H21★, H22 or H25 may be used at some sacrifice of toughness. The extreme heat and mechanical shock usually rule out H24, H41, H42 or H43 for piercers or punches except for some special high-production runs.

Crowners or Punches subject to mechanical shock may be made of S1★ steel when contact with the hot forging is so brief that red hardness is of slight importance. For greater red hardness, H11★, H12★ or H13 may be used with excellent results at hardnesses in the range Rockwell C 40 to 45. Seldom do these tools require the expensive tungsten or molybdenum steels.

Cutoff Tools and Trimming Dies require high hardness and abrasion resistance; red hardness may be important, depending on the operation. For light work S1★, H11★, H12★ or H13 may be used at Rockwell C 47 to 52. For more severe operations H16, H20★, H21★ or H22, and for the most severe, H24 or H26, may be considered. It is seldom the latter steels can be justified for shears and trimmers.

Nut Dies require a compromise among toughness, red hardness, resistance to heat checking and abrasion and may be made from steels H11★, H12★, H13, H15, H20★, H21★, H22 or H26. The listing is generally in the order of increasing cost and increasing serviceability but specific jobs may best be served by one or two of the intermediate steels, such as H20★ or H21★. Usual hardness for this group is Rockwell C 43 to 48.

Surface Condition of the treated tool is extremely important. Because the highly alloyed steels require high heat treating temperatures, the actual carbon content at the surface may be far from the anticipated value. Carburization or decarburization during treatment must be scrupulously avoided if maximum strength, toughness and resistance to abrasion and heat checking are to be realized; accurately controlled atmosphere furnaces or salt baths are highly advantageous. Lacking such equipment, pack hardening may be necessary. An excellent variant of pack hardening is to copper plate the tool and then to heat it in a carburizing medium to the hardening temperature. With these precautions, prolonged soaking for maximum carbide solution will not damage the tool if hardening temperatures are below 1900 F.

Whenever possible, the surface oxide remaining after heat treatment should be left on the tools (unless scaling has been excessive) as it retards seizing and galling. If grinding or polishing exposes bare metal, the tools should be reoxidized by heating in air for about 30 min at about 50 F below the tempering temperature.

Double tempering is effective in relieving stresses—an important factor

in tool breakage. Careful preheating of tools before being started in service pays dividends in reduced breakage. Lubrication, proper mechanical adjustment, and cooling of tools in service are other important but specialized phases promoting satisfactory tool life.

Heat Treatments are given on page 668 of the 1948 Metals Handbook.

Tools for Trimming

Cold trimming usually means trimming of metal flash at room temperatures but may also include operations up to about 300 F. Hot trimming refers to work on material above 1000 F. Trimming at temperatures between 300 and 1000 F is usually considered a hot operation when the tools are being selected.

Hot operations require steels with good resistance to softening at elevated temperatures, whereas cold operations require greater toughness and wear resistance. The required ratio of toughness to wear resistance depends on the irregularities of thickness, the hardness, shape and surface conditions of the metal being trimmed, and on the quantity of production.

Hot trimming of heavy irregular flash requires toughness primarily, and steels S1★, H11★ and H12★ may be used, respectively, as the temperature increases from warm to hot. Steels H14, H21★ and H22 are used above 1000 F. Steel IV-A2 is now virtually obsolete for trimming applications.

Where the toughness requirements are not so severe, but high resistance to abrasion at elevated temperatures is important, steels H24 and H26 are desirable. Where temperatures are in the range 300 to 1000 F, and the flash is uniformly thin, and extreme accuracy is required, it is sometimes desirable to use a cold work tool steel such as A2★ or D2★.

Tools for hot trimming are generally used in the hardness range Rockwell C 47 to 57, the softer being more suitable where extreme toughness is indicated, and the harder where accuracy and wear resistance are most important.

Cold trimming of heavy irregular flash requires toughness, and steel S1★ is recommended. Where long runs under fairly uniform conditions are involved and resistance to wear is the principal concern, steels A2★, D2★, H26 and H42 are preferred. If production runs are short and other conditions fairly moderate and uniform, steels W1★ or O1★ are satisfactory.

The usual hardness range for cold trimming tools is Rockwell C 52 to 62, with the harder ones preferred for long runs under uniform conditions and the softer for irregular shapes and higher toughness.

Heat Treatments for trimming tools are discussed on page 669 of the 1948 Metals Handbook.

Tools for Hot Extrusion

Hot extrusion involves severe conditions of temperature, pressure and abrasive wear, which depend on the metal being extruded.

For extruding aluminum or magnesium, both relatively soft and low-melting, the dies, mandrels and dummy blocks are usually made from

H11★ or H12★.

Tool Steel Selection

For high brasses and leaded brasses, the same steels and one of higher tungsten content are recommended:

H11★, H12★ and H21★.

The harder, more abrasive copper alloys such as cupro-nickel and silicon bronze are extruded at higher temperatures and pressures, and may require steels of higher red hardness and wear resistance. Recommendations vary for the different tools, as follows:

Dies H14, H21★, H22, H26
Mandrels^(a) H11★, H12★, H21
Dummies H14, H21★, H22

(a) Mandrels made from H21 should not be water quenched.

Hot extrusion of steel is still relatively new and selection practices are not firmly established. Steels H21★, H22 and H26 are sometimes used. The problems are similar to the more severe applications of tools in hot forging machines, discussed in the preceding section.

Table VI. Hardening and Tempering Treatments for Hot Extrusion Tools

Steel	Preheating Temperature, deg Fahr	Hardening Temperature, ^(a) , deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr	Hardness, Rockwell C
H11★.....	1400 to 1450	1800 to 1850	Air	1000 to 1100	53 to 43
H12★.....	1400 to 1450	1825 to 1875	Air	1000 to 1200	53 to 30
H14.....	1400 to 1450	1900 to 1950	Air	1050 to 1200	53 to 40
H21★.....	1500 to 1550	2100 to 2150	Air or interrupted oil	1050 to 1250	52 to 33
H22.....	1500 to 1550	2150 to 2200	Interrupted oil	1100 to 1250	53 to 37
H26.....	1500 to 1550	2150 to 2250	Oil, air or molten bath	1100 to 1250	53 to 42

(a) Time at temperature: 20 to 40 min for the first three steels; 15 to 30 min for the last three.

Design factors are important in selection; extruded shapes having sharp corners, wedge designs and adjoining thin and thick sections require tools of high toughness. Dies for extruding these and other intricate sections are used at hardnesses of Rockwell C 32 to 45. The lower part of this range (32 to 40) is applicable for steels H21★, H22 and H26 where extreme toughness is required; the higher part (40 to 45) is applicable for H11★, H12★ and H14. Dies for regular sections, such as tubes or solid rounds, are used at Rockwell C 45 to 50.

Mandrels for brass and copper extrusion are used at Rockwell C 42 to 46 and are normally water or oil cooled in service. Mandrels for aluminum and magnesium are used at Rockwell C 50 to 55 and are not water cooled.

Dummy blocks are used at Rockwell C 40 to 46, the higher alloy compositions such as H21★ and H22 being held to the low side of this range.

Improper alignment of the tool assembly promotes nonuniform stresses and results in premature failures. The importance of preheating the tools and providing proper lubrication must also be carefully considered; well preheated dies, mandrels and dummy blocks are less susceptible to cracking and heat checking in service. If water cooling is involved, the high-tungsten steels should be avoided, as premature cracking and breaking will occur.

Heat Treatment. Hardening and tempering treatments are given in Table VI.

Dies for Drawing Wire, Bars and Tubes

Except for odd sizes and small lots, steel dies for the drawing of wire have been largely replaced by tungsten carbide. The same is true of dies for cold drawing bars, except the larger sizes, rectangles and intricate shapes. In the drawing of tubes, except for the small-

Table VII. Hardening and Tempering Treatments for Wire, Bar and Tube Drawing Dies

Steel	Hardening Temperature, ^(a) , ^(b) deg Fahr	Tempering Temperature, deg Fahr
W1★, W2★	1450 to 1500	350
F2, F3	1475 to 1525	350
O6	1475 to 1525	350
D2★, D4★	1800 to 1875	400 to 450

(a) Steels D2 and D4 should be preheated at 1500 F; preheating is not required for the other steels.

(b) Quenching Mediums: For W1, W2, F2 and F3—water or brine; O6—oil; D2 and D4—air.

dies, W1★ and W2★ can always be used if the requirements for production are not severe but F2 and F3 are preferred because at least twice as much production between redressings can be obtained as with W1 or W2. For the more severe jobs where abrasion and resultant frictional heat are present, D2★ and D4★ are preferred. W1, W2, F2 and F3 will shrink or close-in the hole slightly in hardening, so that slight wear can be compensated for by rehardening, whereas the D2★ and D4★ steels will tend to expand in hardening, so that when worn, they have to be reworked to the next larger size. The first-mentioned steels, if properly hardened, will have a soft tough core, whereas the latter two are through-hardened, hence more likely to fail under excessive pressures or shock.

Hard chromium plating, 0.0015 to 0.0025 in. thick, increases die life from 2 to 5 times, depending on the material being drawn.

Heat Treatment. Hardening and tempering treatments are given in Table VII. The W and F steels should be quenched on a fixture designed so the coolant is circulated through the hole or working part of the die. This method leaves the remainder unquenched and soft and insures the desired shrinking of the hole and soft backing. Simple fixtures clamp the die so that all surfaces are protected from the cooling liquid except the hole through which the water or brine is forced under pressure.

Solid Shear Blades

The selection of steel for solid shear blades is governed primarily by the thickness and temperature of the metal to be cut. Thickness ranges are defined and related to products in Table VIII.

Cold Shearing. For occasional shearing of thin metals in small tonnage,

Table VIII. Steels for Solid Shear Blades

Thickness Category	Thickness Range, in.	Products Sheared	Steel
Cold Shearing			
Thin work	$\frac{1}{4}$ in. or less	Strip, sheet, tin plate	W1★, W2★, D1, D2★, D4★
Medium work	$\frac{1}{4}$ to $\frac{3}{4}$ in.	Bars, shapes, plate, strip	W1★, W2★, D1, D2★, D4★, A2★, L6
Heavy & extra heavy work	$\frac{3}{4}$ in. or more	Bars, billets, plate	S4★, VIF3
Hot Shearing			
Medium work	$\frac{1}{4}$ to $\frac{3}{4}$ in.	Bars, strip, sheet	D1, H11★, H12★
Heavy work	$\frac{3}{4}$ to 4 in.	Bars, billets, sheet bar	S1★, S5★, H11★, H12★, H20★, H21★
Extra heavy work	4 in. or more	Billets, blooms, slabs	S1★, S5★, H11★, H12★, VIF2

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

Tool Steel Selection

W1★ or W2★ would usually be selected; they combine simplicity in hardening with low cost. If production cutting is involved or if the work is abrasive, steels of the high-carbon high-chromium type would be used, such as D1, D2★ or D4★.

For cutting metal of medium thickness the same grades may be used but tempered to a lower hardness to avoid chipping of the cutting edge. Some sacrifice in wear resistance must be accepted. In addition, A2★ or L6 may be used, particularly where greater toughness is desired and wear resistance can be sacrificed. Of the seven steels, probably L6 would show the greatest toughness and resistance to chipping of the cutting edges.

For extra heavy or heavy materials, fine cuts are not involved and it is unnecessary to maintain a keen cutting edge. Hence the shock-resisting steels are employed, such as S4★ or a modification of L6 listed as VIF3 in the ASM classification.

Hot Shearing imparts some heat to the cutting edges of the shear blades. Therefore, steels must be selected that will resist softening under heat. For medium gages, heating is moderate and little shock resistance is needed. D1, H11★ and H12★ are usually recommended, D1 for the lighter gages and greatest production runs, and H11★ and H12★ for heavier gages or lesser runs.

Heating from heavy materials will be greater and more shock encountered. Where temperatures are on the low side and shock is considerable, S1★ and S5★ are preferred. For the hotter metal, H11★, H12★, H20★ or H21★ would be selected, the first two where shock is the greatest and the last two to withstand the most heat.

For extra heavy materials, as much heat may be involved as in the previous group, but the shock will be considerably greater. Hence the more shock-resisting steels such as VIF2, S1★, S5★, H11★ or H12★ are used with some compromise on heat resistance.

Heat Treatment of solid shear blades is discussed on page 669 of the 1948 Metals Handbook.

Blanking and Piercing Dies

"Blanking" is the shearing of a shaped part (a blank) with a completely enclosed periphery, from strip, sheet or plate. The cutting of a shaped hole within a blanked part is called "piercing". The material is usually sheared by a moving blade (punch) and a fixed edge (die).

Blanks are made from almost every flat rolled material, ranging from paper to high-silicon electrical steel. Thicknesses vary from less than 0.001 to more than 1.0 in. Work temperatures may exceed 1500 F. A blank may be a simple circle or a shape more complicated than a snowflake.

The selection of tool steel is of secondary importance compared with the proper design and construction of the die. Many examples could be given to illustrate how die life has been doubled or tripled while using the same tool steel with a better designed and constructed die. The most im-

portant design and construction factors are: (1) well-guided punches, (2) proper clearance between the punch and die in relation to the thickness of material being punched, (3) accurate alignment of punch and die, (4) compound die construction where sharp corners are necessary, (5) heat treatment of the die to optimum hardness, (6) grinding off decarburized surfaces, and (7) careful grinding to minimize softening and residual tensile stresses on the cutting edges.

After the proper design and construction methods have been established, the tool steel should be selected with reference to these principles:

- 1 Machinability generally decreases as the carbon and alloy contents increase.
- 2 Wear resistance is directly related to the carbon content and the presence of carbide-forming alloying elements.
- 3 An increase in wear resistance is usually accompanied by a decrease in toughness.
- 4 Distortion and quench cracking decrease as the severity of the quench decreases.

With the last of these principles in mind, the applicable tool steels may be divided into the following four categories:

Water-Hardening	Oil-Hardening	Air-Hardening
W1★	O1★	A2★
W2★	O2	A4
W3	O6	A5
W4	O7	A6
W5	S1★	D1
W6	S5★	D2★
W7	D3★	D4★
S2	D6	D5
S3		
S4★		
	High Speed	
	H26	
	H42	
	M2★	
	T1★	

Water-Hardening Steels are the most popular for piercing and blanking dies; machinability is good; wear resistance can be controlled by varying the carbon from 0.60 to 1.40%. The shallow hardening characteristic produces a hard surface with a softer and tougher core in sections over $\frac{1}{2}$ in. A minimum of heat treating equipment is necessary.

Unfortunately, water-hardening steels distort and may crack during hardening. This is aggravated with variable section sizes, sharp corners, blind holes or complicated shapes. It is impossible to predict the dimensional changes in advance, primarily because of the variable amounts of core and case. Variables affecting case depth are too numerous and complex to cover here.

Care should be taken in grinding, because the hardness of these steels falls off quickly above 350 F. With ordinary grinding methods, surface softening can easily occur.

W1★, W2★ and W4 are available in carbon contents from 0.60 to 1.40%, in 0.10 ranges, and would be chosen according to the wear resistance or toughness required. Small amounts of chromium are present in some of the steels to increase the hardenability, thus making them suitable for larger sections. Vanadium is added to some, to minimize grain growth where higher quenching temperatures are used for increased hardenability or where control of quenching temperature is poor or erratic.

The S steels are used mainly for punches whose cross section is so small that water-hardening steels do not give the favorable case-core effect. Punches for piercing holes of diameter approaching the thickness of the material being pierced require exceptional shock resistance, and S4★ is the most commonly used steel. A slight improvement in wear resistance is obtained when tungsten is added (S3). These steels can be oil-hardened in moderate sections from higher than normal quenching temperatures.

Oil-Hardening Steels. Dies with sharp corners, complex shape and variable section size have been successfully made from oil-hardening steels with a minimum of breakage and distortion during hardening. The low quenching temperatures and the relatively mild quench reduce the residual stress in the hardened dies. Because the dies harden throughout the section, the amount of dimensional change obtained is more predictable, which permits closer finish machining and reduced finishing costs. The toughness of water-hardening steel in sections over $\frac{1}{2}$ in. is absent in oil-hardening steel. Care must be taken to prevent softening and cracking during grinding.

Oil-hardening steels fall naturally into two categories, the low-alloy grades of the O and S groups and the highly alloyed grades of the D group. The wear and abrasion resistance of the low-alloy steels is not much better than the equivalent water-hardening die steels. Most of the alloying elements are used to increase hardenability rather than to form carbides.

Steel O1★ is for general utility. The other steels of group O are used for their special characteristics. Hardening of O2 can be accomplished with a minimum of distortion but some wear resistance is lost. Better wear and abrasion resistance is obtained with steels O6 and O7 but more distortion can be expected.

The oil-hardening S steels are similar to the water-hardening steels of the same class. S1★ will have the best combination of toughness and wear resistance. S5★ is somewhat tougher than S1★ but has less resistance to wear and abrasion. Both are popular for tough punching applications. The S steels are not considered "nondesigning" because the hardening temperatures are quite high.

The highly alloyed oil-hardening D steels have excellent resistance to wear and abrasion. They are used for high-activity dies where the additional machining, grinding and material costs are justified by the long life obtained. Steel D3★ is the common grade; D6 was developed for extreme resistance to wear and abrasion. The high quenching temperatures required for full hardening cause troublesome distortion, particularly with complex dies. These steels are similar to the air-hardening grades of the same class, and the difficulties mentioned below for the latter will obtain for both types.

Air-Hardening Steels. Dies and punches with sharp corners, variable section size, blind holes and complex shapes can be safely hardened with minimum breakage, distortion and dimensional change when the air-hardening steels are used. The alloying elements added to increase hardenability usually form carbides which

improve resistance to wear and abrasion.

These steels are the least machinable of all tool steels, even in the annealed state, and machinability decreases with increasing carbon content. Although the danger of softening during grinding is minimized by the addition of alloying elements, the improved wear resistance hinders grinding and increases the incidence of grinding cracks. A soft, well dressed wheel should be used.

The cost of air-hardening tool steels is greater than for those previously discussed, though less than for high speed steels. However, added expense is often justified by the increased die life and reduced quench cracking.

Quenching temperatures for air-hardening steels are usually higher than for the other grades mentioned so far. This necessitates controlled atmosphere furnaces, or the tools must be packed in spent pitch coke or cast-iron chips.

Air-hardening steels can be divided into two groups, the medium-alloy and high-alloy. In the former group the most common is A2*, which has good wear resistance and is used extensively for medium-activity dies where the superior wear resistance of the higher-alloy steels is not required. The others in this group are less wear resistant than A2* and are used where extreme accuracy after hardening is required; A6 is for applications which require a combination of good shock resistance and low distortion after hardening.

The high-alloy air-hardening steels were developed to provide maximum resistance to wear and abrasion. They are difficult to machine and to grind. D2* is the most popular, but D4* is rapidly gaining favor, especially for highly abrasive applications. Carbide-forming elements such as cobalt and tungsten are added to improve the wear resistance further; these variations are typified by D5 and D6. All these are extremely difficult to grind, and a minimum allowance for grinding should be made.

The most popular air-hardening steel for high-activity dies is D2*, which has excellent edge strength, good abrasion resistance and can be hardened with minimum dimensional change.

Steel D4* and high-vanadium and cobalt variations of this grade are used for extremely abrasive applications—for instance, punching laminations of high-silicon steel.

High Speed Steels and Special Processes. Many materials must be blanked and pierced when hot. High-activity dies for these applications are often made from low-carbon high speed steels H26 and H42. For additional information concerning high-temperature applications, the reader may consult the sections of this article on tools for forging machines and tools for trimming.

Cold blanking dies made from carburized high speed steel have excellent life. Often the increased die life more than pays for the extra material, machining and heat treating to make the die from high speed steel.

Pack carburizing is the most com-

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

mon method of case hardening high speed steel although gas carburizing is increasing in popularity.

The typical pack carburizing treatment outlined below is satisfactory for both M2* and T1*:

- 1 Pack in carburizing compound.
- 2 Hold 2 hr at 1650 F.
- 3 Raise temperature to 1950 F and hold for $\frac{1}{2}$ hr after temperature is uniform.
- 4 Quench in a salt bath at 1100 + 70 F; hold until the part has cooled uniformly to the bath temperature; remove and cool in still air to 200 F or lower.
- 5 Temper 2 hr at 1025 F, cool to room temperature.
- 6 Repeat the tempering treatment twice, since triple tempering is required to transform all the austenite in the case.

Since size change or distortion is very slight with this treatment and case depths are relatively shallow, it is both practical and essential that only the minimum amount of stock be allowed for grinding after hardening.

Punching thin materials requires dies with small clearances. Expert tool makers and expensive machining and grinding equipment are required to make such dies from hardened tool steel. For short production runs, for experimental runs or for plants with inadequate toolmaking facilities, it is often advisable to use soft or semi-hard dies with hardened punches.

The soft die is machined slightly oversize, after which the punch and die are mounted in the press. The punch is raised out of the die. The cutting edge of the die is "caulked in" with a ball-peen hammer. The punch is then lowered to "shear in" the die. This process is repeated whenever the burr on the blank becomes excessive. Virtually any unhardened or moderately hardened steel can be used for the "soft" die. Maximum die life using this method can be obtained with high speed steel dies hardened to Rockwell C 33 to 38.

It should be emphasized that this is an expedient not to be employed for high-activity items.

Further information on the heat treatment of piercing and blanking dies is given on page 671 of the 1948 Handbook.

Press Forming Dies

Dies for the press forming of simple contoured parts, and parts with balanced sections that have few blind holes or holes near the edges, can be safely made from the straight-carbon and carbon-chromium tool steels, W1*, W4 and W5. Steels of this class are usually employed in the form of inserts in a cast-iron shoe. If of very simple design, they may be fastened to a steel or cast-iron die plate. For die or punch sections thicker than 3 or 4 in., the lower carbon ranges (0.75 to 0.85%) are recommended, preferably with small percentages of chromium to improve the hardenability and core properties after heat treatment.

These steels machine well in comparison with most tool steels and produce hard, wear-resistant and score-resistant surfaces when heat treated. However, they have limitations as to the number of reworks or surface dressings, because of their shallow hardening characteristics. As the intricacy of the die and punch increases or as higher production is required,

other steels should be considered, such as the oil-hardening O1* or O6, which are much safer to harden because of the less severe oil quench. Distortion is also less and there is some improvement in wear properties at the same hardnesses, compared with carbon steels. For high-production dies and dies of such shape as to be hazardous in either a water or oil quench, the air-hardening steels such as D2* or D4* should be used, and neutral hardening is required to prevent heavy decarburization. A small growth in overall dimensions usually occurs. The steels have excellent wear resistance. Die rings and punches are sometimes cast to shape from these two steels, which saves considerable machining in bringing the dies to finished size.

For some severe forming operations where the press operation requires heavy bottoming blows to form the part fully, a steel suitable for a hammer die-block is used, such as L6 or ASM VIF2, generally flame hardened on the working surfaces. These also are sometimes cast into a solid die or punch, or they may be forged into inserts which are machined and fitted into a low-carbon steel or cast-iron die shoe. The working surfaces and especially the draw radii are then flame hardened to about Rockwell C 45 to 50. If production requirements are low these dies may be used as normalized, without further treatment. These steels work harden rapidly to produce a smooth working surface which favors good surface finishes on the stampings.

Heat Treatments are discussed on page 671 of the 1948 Metals Handbook.

Press Drawing Dies

The press drawing or deep drawing of sheet metal can be divided into two categories, as follows:

Category 1. Flowing light-gage sheet metal into a die by a punch, draw ring and blank holder that restrict the flow of metal only enough to stretch it around the punch and to set it permanently in this form. A minimum of ironing-out and reduction of thickness is obtained. Subsequent annealing is not required except for some nonferrous metals where restriking of corners or flanges is necessary or where stress-corrosion cracking might later become a problem.

Category 2. Forcing heavy-gage sheet metal or plate into a die by a punch, generally without a blank holder, restriction of the metal being obtained by having the clearance between punch and die slightly less than the metal thickness. The form is obtained by a combination of flowing and elongating of the metal. This may be done in one die or a series of dies, depending on the depth of draw. When more than one draw is made, intermediate annealing is generally required. Heavy reduction of cross-sectional area and ironing-out occur.

There is a wide difference in the tool materials needed for these two categories. The extent of production (short, medium or long runs) and the cost of available die materials also are important in selecting the one that will most economically produce satisfactory parts over the required production schedule.

Category 1—Low Production. Tool requirements are high resistance to frictional wear and to galling; low strength is usually sufficient. Gray cast iron is generally satisfactory, with a tensile strength of 25,000 to 30,000 psi, such as SAE 120 or 122 (ASTM class 25

Tool Steel Selection

or 30). Other costlier materials may be used, such as water-hardening or oil-hardening tool steels W1*, O1* or O2. Rubber hydroform dies have been used successfully where a very short production run is scheduled, as for aluminum aircraft parts. Certain types of plastic dies are now being tried on short runs.

Category 1—Medium Production. Higher strength is needed than for low production and the die surface should be flame hardenable. Alloy cast iron having a tensile strength of 40,000 to 50,000 psi, such as ASTM class 40 or 50, is suitable. Dies for medium production may have hardened steel inserts in the draw ring or lower-shoe draw surface. Inserts of simple design and balanced section may be made of water-hardening W1*, usually hardened and tempered to Rockwell C 58 to 60. Unbalanced or odd-shaped sections, corner inserts and the like are usually made from oil-hardening tool steels. On small dies such as cupping dies and small progressive draw dies which need higher strength and wear resistance than alloy cast iron will give, the punch, die and blank holder are often made of oil-hardening tool steel. These, as well as the inserts for iron dies, are made from O1*, O2, O6, L6 or L7. Hardness of the heavy sections is generally held to Rockwell C 55 to 60; light sections, small punches and dies are Rockwell C 58 to 62.

Category 1—High Production. High-strength alloy irons are suitable for many high-production operations but are usually arranged with tool steel inserts around the working areas. Iron having a tensile strength of 45,000 to 60,000 psi, such as ASTM Class 50 or 60, is recommended. Flame hardening the draw surfaces including the draw radii is beneficial. Inserts are usually made from tool steels O1*, O6, A2* or D2*. On the more severe draws where heavier gage metal is being worked, dies and punches are made from D2*, A2*, D5 and L6, generally cast to approximate shape, then finish machined and heat treated to about Rockwell C 58 to 62.

Category 2. Regardless of the production rate, this category represents severe service. Dies in this class are always made from steel and sometimes have sintered carbide wear rings assembled in the draw area. High-carbon high-chromium steels D2*, D3* and D5 are the most widely used. In the more severe draw operations high speed steels M2* and T1* are sometimes used because of their high compressive yield strength and ability to resist scoring and pick-up. On less severe draws the low-manganese oil-hardening O1* may be used. Other steels found satisfactory are O6, A2*, O2 and L6.

Coining Dies

Cold coining is a severe test for any die steel and requires high toughness, compressive yield strength, wear resistance and resistance to chipping. Light coining may be done satisfactorily with dies made from W4, W5, W6 or W7 at Rockwell C 58 to 62. More severe coining may require the deeper-hardening steels such as A2*. If higher wear re-

sistance and compressive yield are required, it will be necessary to go to the high-carbon high-chromium D2*. Best results will be obtained from this steel at about Rockwell C 56 to 59. Other steels, though classed as hot work steels, are sometimes used for coining dies and punches; for example, H11*, H12*, H20* and H21*. These exhibit fair to good wear properties with excellent toughness when used at or near their full hardness of Rockwell C 50 to 54. For coining dies having circular grooves, beads or thin sections, the last mentioned perform better than the higher-carbon steels.

Heat Treatment of coining dies is included in the article on page 671 of the 1948 Metals Handbook.

Cold Extrusion Dies

Cold extrusion, one of the most difficult operations performed with tool steels, is of three principal types: forward extrusion, combined forward and backward extrusion, and backward extrusion. In the first, a solid slug of metal is trapped in a die cavity and sufficient pressure exerted to cause the metal to flow through an opening in the bottom of the cavity, the opening having the shape of the desired cross section. The punch fits the chamber. The second is similar except that sufficient restriction is obtained by design of the die and punch to cause part of the metal to flow through the opening and part to reverse and flow up and around the punch, through the annular space between punch and chamber. The third is accomplished by causing all the metal to flow up and around the punch (or punches, if a double-end reverse extrusion is being made).

For Dies, wear resistance and toughness to withstand outward pressures are most important. Inserted dies are more economical than solid dies, and are the most commonly used. For die inserts where production schedules are low, carbon tool steel W1* is satisfactory, at Rockwell C 61 to 63. These inserts give the best performance when fixture-quenched to harden around the hole through the die. For high-production runs, high-chromium die steels D2*, A2* and D5 and high speed steels M2* and T1* are recommended. These are used at hardnesses about the same as the carbon steels, or slightly higher for the high speed steels. The M2* and T1* high speed steels with lower carbon (0.45 to 0.65%) than normal are sometimes used for greater toughness in the insert.

Die Holders and Backing Blocks are very important in an extrusion die and must be of sufficient section size and strength to support the die insert under the required extrusion pressures; otherwise the insert will split. Holders and backing blocks give good service when made from nickel-chromium steels such as L6. The holders are usually hardened to Rockwell C 54 to 56 and the backing blocks to Rockwell C 60 to 63. Another steel satisfactory for these parts has a nominal composition of 0.55% C, 0.45% Mn, 0.25% Si, 3.25% Ni and 2.50% Cr; it is melted on special request.

Extrusion Punches are the most critical of all extrusion tools. They must resist scoring and metal pick-up and must withstand high compressive loads, as well as have toughness to avoid

snapping off under pressure or slight misalignment. Very little latitude can be allowed in the materials for punches except on some forward extrusions with nonferrous metals, where the pressures are somewhat lower. The best results are obtained with punches of M2* high speed steel at Rockwell C 61 to 63. As a second choice, T1* high speed steel is recommended at Rockwell C 60 to 61. A carbon content of 0.50 to 0.65% in the tungsten steel is beneficial in obtaining the toughness required.

For some forward extrusions where the reduction of area is not great and lower pressures are required to push the metal through the die, high-carbon high-chromium D2* or D5 can be used. These have to be at full hardness, Rockwell C 61 to 62, to resist scoring and pick-up. On backward extrusion of steel, where metal displacement is high, these tool steels will upset and swell in the shank. For light forward extrusions of steel and for both forward and backward extrusions of nonferrous metals, the tungsten finishing steels, F2 and F3, have been satisfactory. Rockwell C 62 to 64 is recommended.

Recently, sintered carbide has been used increasingly; it has very high compressive strength and excellent resistance to scoring and metal pick-up. Low impact strength is its one major disadvantage, but this can be partially overcome by designing dies and punches to line up more accurately. Die insert sleeves of carbide have proved successful in cold extrusion, especially on dies for tapered bolts.

The carbides recommended for extrusion tools are the high cobalt grades (16 to 20% Co). Some suppliers prefer to add about 4% Ta. Hardness is Rockwell A 86 to 88.

Cold Heading Dies

Probably 90% of the cold heading dies can be made from a shallow-hardening steel such as the water-hardening carbon tool steels with or without chromium and vanadium:

W1*, W2*, W3, W4 and W5 with carbon contents from 0.85 to 1.10%.

The requirements of cold heading dies include high hardness, to provide a reasonable degree of wear resistance, but more particularly a very high toughness to resist the impact loads and high spreading forces encountered in service. High toughness means either resistance to repeated impact loads or capacity for some plastic deflection prior to breakage—thus some inherent ductility.

The stresses at the surface of cold heading dies are extremely high and approach the yield strength of the strongest tool steels. By heat treatment to provide a hard case and a softer core, compressive stresses remain in the hard case that counteract part of the tension stresses of service and permit a higher actual working load before failure. The water-hardening tool steels perform best for this reason. Often only the working portions of the die will be hardened, by directing a water or brine spray at these portions during the quench. The surface hard-

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

ness can thus be kept above Rockwell C 60 while the core will be C 40 to 50, and in extremely large dies may be as low as C 35.

Importance of Hardenability. The level of compressive stresses introduced into the surface of the heat treated die is a function mainly of the depth of hardening of the die, and thus of the hardenability of the steel from which the die is made. Cold heading die steels should always be purchased to a specified hardenability level which has proved satisfactory for the specific application, or the application should be detailed so that the vendor may select the proper hardenability for the size and design of the die.

Small cold heading dies of the solid type, with the working portion in the center and with a maximum outside diameter of less than 2 in., can be satisfactorily made from a steel having a penetration characteristic of 7 to 9 on a $\frac{1}{2}$ -in. round P-F test specimen. (See page 418, 1948 Metals Handbook.)

Large solid cold heading dies, such as those used to form wire in the range of $\frac{3}{4}$ to $\frac{7}{8}$ in. diam, and having a maximum outside diameter of approximately $3\frac{1}{2}$ to $4\frac{1}{2}$ in., are best made from steels having P-F hardenabilities of 10 to 12 or higher, depending on the application.

Open dies (usually made from squares with an impression on several faces) are generally made from deeper-hardenning steels than those for solid dies for an equivalent wire size.

If the case is too thin, there will not be enough strength to resist the compressive stresses along the longitudinal axis of the die, and the die will sink and often crack at the radius near the bottom corner of the impression. These failures are avoided by raising the hardening temperature or selecting a deeper-hardenning steel, to provide a greater case depth. The same principles guide in selecting a steel for dies for severe extrusion operations. If the case is too deep, gross breakage may result because of brittleness caused partly by the automatic reduction of compressive stresses in the surface of the hardened case.

Grain Size and Composition. The selection between a carbon steel and a carbon-vanadium steel depends on whether the added grain size protection and probably higher fatigue strength of the vanadium steel is worth the slightly higher cost. Ordinarily steel W1 \star is more readily available with a carbon content of 0.95 to 1.10% and W2 \star with 0.85 to 1.00% C. Both are available in a range of hardenabilities by special arrangement, and are commonly available in stock in a medium hardenability range. As regularly stocked, W2 \star is usually shallower-hardenning than W1 \star . Steels W3, W4 and W5 are available for special purposes. W3, containing high vanadium, retains an extremely fine grain up to hardening temperatures of 1750 F, and the depth of hardening can be varied safely over a wide range by adjusting this temperature. Steels W4 and W5 contain chromium for deeper hardenability, useful in large dies or where specific performance data have proved that such hardenability is required.

Alloy Steels. Because of their low alloy content, the wear resistance of carbon tool steels is distinctly limited, even at the maximum allowable hard-

nesses of Rockwell C 62 to 64. More highly alloyed steels have the disadvantage of deeper hardening, so that advantage can no longer be taken of the case-and-core effect. Such deep-hardenning steels as A2 \star , D2 \star , T1 \star , M1 and M2 \star can therefore be utilized only where the stresses imposed are light, where overloads are not apt to be encountered, or where high stresses are tolerated only because of special die designs. In only a very few instances can such steels be employed as solid cold heading dies, unsupported by die holders. These usually are for heading long runs of small wire in dies generally not over 2-in. outside diameter.

When parts of intricate design must be cold formed and where the production must be high, then these steels are applicable in the form of inserts which are suitably shrunk or fastened into a holder, quite commonly made from a steel similar to H11 \star or H12 \star , to provide the necessary support. The holder steel is frequently treated to Rockwell C 48 to 50. It is, of course, important that the insert be fitted carefully into this holder by pressing or shrinking; otherwise, cracking in service will result. The choice between these various alloy steels depends on the wear resistance and life desired. Steel A2 \star would be of general application for medium life, whereas the high-carbon high-chromium D2 \star or the high speed steels would be used for maximum life. These are only several of the possibilities; any deep-hardenning cold work die steel is usable.

Heat Treatment of cold heading dies is discussed on page 672 of the 1948 Metals Handbook.

Thread-Rolling Dies

A thread-rolling die must be hard enough to withstand the forces in forming the thread, and must have wear resistance and sufficient toughness to adjust to stresses developed. These dies usually fail by spalling and breaking down of the thread crests, which roughens the minor diameter and makes the product unusable. Failure is probably caused by fatigue stresses resulting from slight die misalignments and by spring in the machine. Best product and maximum die life can be obtained only when the dies are properly set up and when the correct die speed and number of blank revolutions are used for the material being worked. These factors may be as important in die life as the specific steel chosen for the dies.

The steels most commonly used for thread-rolling dies are

A2 \star , D2 \star , M2 \star and T1 \star .

Other high-carbon high-chromium steels are used less often than D2 \star . Both the high-carbon high-chromium steels and the medium-alloy A2 \star are widely used for general work. The high speed steels are for the most difficult jobs, long runs, threading of heat treated stock, and particularly for circular dies. Some manufacturers of high speed steel thread-rolling dies prefer to use M2 with 0.75% C and T1 with 0.60% C (about 0.10% less than the typical carbon contents for these steels) to secure greater toughness with still adequate hardness. The steel chosen should be well annealed and have

as uniform a carbide distribution as obtainable for the bar size and composition.

Size Change During Hardening. "Cut" dies are not machined after hardening and must have a predictable or minimum size change in hardening. It may be necessary to compensate for this change when milling the form. The high-carbon high-chromium D steels and the medium-alloy A2 \star show the least size change. The air-hardening D2 \star and A2 \star have less tendency to "bulge" in hardening, causing a "rock" in flat dies, than do oil-hardening tool steels. If the dies are form ground after hardening, size change is of less importance.

Ease of Machining. The hobs used to mill the form on thread-rolling dies are expensive tools, so easy-machining die stock is desirable. The high-carbon high-chromium D steels are the most difficult to machine or grind, the 2.25% C steels being a little more difficult than those with 1.50% C. The high speed steels T1 \star and M2 \star are easier to mill and may be ground with less hazard. The medium-alloy A2 \star is easiest to machine.

Abrasion Resistance and Toughness. All the steels listed have good resistance to abrasive wear. The high-carbon high-chromium steels are the best, followed by the high speed steels and then the medium-alloy. The 2.25% C grades of high-carbon high-chromium (D3 \star , D4 \star and D6) have better wear resistance than the 1.50% C D2 \star and D5. Toughness is in about reverse order.

Machining. All decarburization and surface defects should first be removed from the stock, not only on the working face, but on all other surfaces as well; otherwise, the dies will crack or warp in hardening. Feeds and speeds in milling should be chosen to give the smoothest possible finish. If dies are ground after hardening, care must be taken to prevent burning, with resultant softening or cracking.

Hardening. The available hardening equipment may affect the choice of steel. High speed steels require temperatures of 2150 to 2300 F with either good atmosphere control or a salt bath. The high-carbon high-chromium steels require 1750 to 1900 F with controlled atmosphere or pack hardening. The A2 type is hardened from 1750 to 1800 F with similar surface protection. Hardening and tempering treatments are discussed on page 673 of the 1948 Metals Handbook.

Gages

Gages are hand tools used to measure the dimensions of parts or other tools. They vary from simple length bar gages for measuring rough forgings to highly polished and lapped gage blocks capable of measuring to millionths of an inch. All have one feature in common—they are used at room temperature or, if used in measuring hot parts, the period of contact is so brief that the gage size is not affected by the elevated temperature.

Solid Gages of Simple Design include gage blocks, length, bar and pin gages, and some plug, ring, feeler and height gages. For all of these the steel preferred is

W1 \star .

Tool Steel Selection

which provides the necessary wear resistance on gaging surfaces at low cost, with good machinability and simplicity of heat treatment. Steels

L3, W2★, W5, O2 and O6

at slightly higher initial cost perform as well as W1★ and are recommended as alternates in the order listed.

Surface hardness should be Rockwell C 63 to 65 (except for feeler gages, which should be C 45 to 50, obtained by tempering at a higher temperature than shown in Table IX).

Table IX. Hardening and Tempering Treatments for Steel Gages

Steel	Hardening Temperature, ^(a) deg Fahr	Tempering Temperature, deg Fahr
W1★	1450 to 1500	350
W2★	1450 to 1500	350
W5	1425 to 1475	350
O2	1425 to 1450	325
O6	1475 to 1525	325
D2★	1825 to 1850	400
D4★	1850 to 1875	450
D5	1825 to 1850	400
L3	1500 to 1525	325
135 ^(c)	1700 to 1750	1250

(a) Steels D2, D4 and D5 should be pre-heated at 1450 F. Preheating is not required for the other steels.

(b) Quenching Mediums: For W1, W2 and W5—brine or water; O2, O6, L3 and 135—oil; D2 and D5—air; D4—air or oil.

(c) Nitrallloy 135 Modified—After hardening and tempering as indicated, and after finishing, including lapping, the gage is nitrided in ammonia for 12 to 20 hr at 980 F, to give a case hardness in the range of 900 to 1000 Vickers.

Gages of More Complex Design, such as ring, countersink and snap gages, which may crack or distort in heat treatment if made from W1★, can be made safely and with necessary properties from

L3, O6, O2 and D2★

if carefully heat treated. (Again, steels are listed in the order of preference.)

Master Gages, Master Gears and Male Spline Gages require high accuracy and resistance to wear from frequent usage in checking other gages over long periods of time. This requirement plus the necessity that shrinkage in heat treatment be held to a minimum can safely be met by the higher-alloy steels like

D2★, D5 and D4.

These steels are more expensive in initial cost and in processing, especially in the time consumed in lapping to size. Where some sacrifice in wearing properties can be tolerated,

O2 and O6

can be substituted with little risk of shrinkage.

Male and Female Thread Gages, male spline gages with small delicate splines, and small ring gages require safety in hardening, freedom from grinding checks in the teeth and thin sections, as well as low distortion in heat treatment. These properties are best ob-

tained with the high-manganese oil-hardening steel

O2.

This steel wears well but is inferior in this respect to

D2★, O6 and L3

which should be selected when some of the above requirements are outweighed by the necessity for long life.

Female Spline and Female Thread Ring Gages

Ring Gages are among the most expensive to manufacture because of the hand lapping time required to bring them to size tolerances. (Internal grinding is impractical.) These gages require accuracy and long wear life, a combination that can be obtained with the high-carbon high-chromium steels such as D2★. However, the cost of hand lapping them is very high and wear resistance is sometimes sacrificed for better-working steels like O6 or O2.

Such a compromise can be avoided and excellent wear properties obtained with a minimum of lapping time by a modified Nitrallloy 135 (0.42% C, 1.60% Cr, 0.37% Mo and 1.0% Al), normalized, quenched and tempered to about 320 Brinell, completely finished (including lapping of the gage) and then nitrided. As such a gage is useless when it is worn more than a few tenths of a thousandth, a light case will suffice, sometimes that obtainable in a 12-hr nitriding cycle. Any dimensional change during nitriding will be a slight growth; light polishing will restore the original lapped size.

Combination Gages are made up of several different materials but the commonly used ones are cast iron for frames, bodies and bases, aluminum for handles, bodies and bases, and tool steel and carbides for inserted gaging members or wear pieces. The iron is generally a gray iron of 20,000 to 35,000 psi tensile strength, equivalent to SAE 110, 111 or 120 or ASTM Class 20, 30 or 35. Hardness is 187 to 241 Brinell. Large castings are usually stress relieved at 850 to 900 F.

Aluminum handles for plug gages, male thread gages and ring gage bodies may be either the soft 2S or 3S or stronger alloys such as 24S or 17S. Light weight reduces fatigue of inspectors of production parts.

Bases are sometimes cast from Al-Si or Al-Si-Cu alloys, rather than cast iron, on large gages where dimensions are not held too closely, such as gages to check automobile body dimensions, window openings and the like. Aluminum is not suitable for precision gages because of its high thermal expansion.

The steel used in combination gages for gaging members and wear surfaces requires the same properties as in the solid steel gages discussed above, and selection should be made accordingly. Combination gages may have a slight advantage where a flat or simple shape can be used for an insert rather than a curved or box-shaped piece with cutouts that cause stress raisers and hazards in quenching. In these instances a less costly steel may be applicable. The other advantage is cost savings through the use of less tool steel.

Sintered carbides are being used increasingly for wear inserts. Ring gages

★Stocked in almost every warehousing district and made by the majority of tool steel producers.

are being made with a carbide ring shrunk in a steel or aluminum holder. Gage blocks are being produced from carbide to extremely close tolerances. In using carbide gage blocks in varying temperatures to gage steel parts it is often necessary to use a correction factor because of the difference in coefficient of expansion between steel and carbide. Any of the commercial grades of carbide give superior wear life when used as inserts or gage blocks.

Heat Treatments for gages made of tool steel are summarized in Table IX.

Plastic Molds

Some molds are shaped by hubbing, some by machining, and others by a combination of the two. Steels for each of these applications, as well as for master hubs, are listed in Table X.

Table X. Mold and Hub Steels

Application	Steel	Maximum Hardness (annealed), Bhn
Hubbing molds	P1	90
Hubbing molds and cut molds	P2, P4	110
	P3	131
	P5	100
Cut molds	P20	190
	O1★, O2	201
	H11★, H26	229
Cut molds and master hubs	H12★, A2★, D2	229
Master hubs	S1★, S4★	229
	H25	241

Hubbed Molds. Steel P1 is excellent for hubbing because of the low hardness when annealed. It also work hardens slowly while the master hub is being forced into the soft blank. Molds of this steel are carburized and then water or brine quenched to Rockwell C 58 to 64 on the surface. This steel has very low hardenability, hence extreme care—usually involving the use of jets in the cavity during quenching—is required to obtain uniform hardening. Because of the distortion that accompanies water hardening and the low core strength, molds from this steel are usually limited to large-tolerance, short-life applications requiring medium-sized cavities with low molding temperatures and pressures.

Steels P4 and P5 are slightly more difficult to hub than P1 but the chromium content (5.00 and 2.25%, respectively) increases hardenability and permits oil hardening of P5 and air hardening of P4 after carburizing. The core is harder, and molds made from P5 are suitable for medium-life applications requiring medium mold temperatures and pressures. Steel P4 is the more difficult to hub, but the additional core hardness and lower distortion in hardening recommend it for higher mold temperatures and pressures and for complex, close-tolerance parts.

Steels P2 and P3 are still more difficult to hub, primarily because the nickel content (0.50 and 1.25%, respectively) increases the rate of work hardening. The nickel decreases notch sensitivity. These steels harden in oil after carburizing and are used for medium-sized cavities with medium molding temperatures and pressures. Often a combination of hubbing and machining is used for molds from steels P2, P3, P4 and P5.

Cut Molds. Steel P20 is recommended for applications which require high molding pressures and medium temperatures; hubbing is not recommended because of the high carbon content (0.30%). This grade is usually carburized and oil quenched to Rockwell C 60 to 62 on the surface. Core hardness will vary from C 30 to 50, depending on section size.

Steels O1★ and O2 are oil-hardening grades used for machined molds which will withstand medium temperatures and high molding pressures. They have high abrasion resistance but are low in ductility and notch toughness.

Steels H11★ and H12★ are used for applications that require good notch toughness, high molding temperatures and pressures, medium wear resistance and accuracy in hardening. They can be hardened in oil or air to Rockwell C 52 to 58.

Steel H26 is a low-carbon high speed steel and is used for very high temperature applications such as molding or extruding fluoride-base plastics at 600 to 750 F. Because of the high cost of steel, machining, grinding and polishing, H26 is used only for special applications where the mold life must be extremely long.

Steels A2★ and D2★ are air-hardening grades, employed for molding highly abrasive materials requiring high molding temperatures and pressures. D2★ has the better strength and abrasion resistance. The notch toughness of both is quite low; they are difficult to machine, grind and finish but the accuracy obtained after hardening minimizes the amount of finishing required. Because of the high cost of making molds from these steels, they are usually employed only for extremely long runs.

In recent years there has been increasing use of vinyl-base plastics which break down at the relatively high molding temperatures to release hydrochloric acid; resulting corrosion has been minimized by chromium plating the molds. Since chromium plating also minimizes stripping difficulties, many molds are hard chromium plated even when used to mold noncorrosive plastics. Steel D2★ is often so plated and used for corrosive plastics; for low-activity applications of this type, chromium plated type 420 stainless steel is often used.

Master Hubs. Steels A2★ and D2★ are also used to make master hubs for impressing steels P1, P2, P3, P4 and P5. Their high hardness and abrasion resistance recommend them for high-activity hubs where notch toughness is not a requirement.

Where notch toughness is required, S1★, S4★, H12★ or H25 should be used. Steels S1★ and S4★ are oil quenched after carburizing. Surface hardness of Rockwell C 60 to 63 gives good wear resistance, and the compressive strength of the core is sufficient to withstand hubbing.

Steels H12★ and H25 are used for high-temperature hubbing applications. One specialized process is pressure casting of beryllium copper over a master hub; hot work grades H12★ and H25 withstand the heat with a minimum of heat checking and have adequate red hardness to resist softening.

Heat Treatments for molds and hubs are discussed on page 675 of the 1948 Metals Handbook.

Die-Casting Dies and Permanent Molds

The selection of a material for die-casting dies or permanent molds depends primarily on the casting temperature of the alloy being cast.

Of the many steels that are used, the following have found principal commercial application:

L2, L6, P20,
H11★, H12★, H13, H20★, H21★ and H23.

Gray cast iron, 1020 and 1045 carbon steels, Nitralloy G and type 410 stainless steel are typical of some other materials used.

When casting zinc, lead or tin alloys the operating temperatures are relatively low, and for short runs carbon steels can be employed without heat treatment. For large dies or for long runs, steels L2, L6 or P20 may be utilized. Their alloy content provides hardenability to resist higher operating pressures and often permits heat treatment of the finished dies, or of the blocks from which the dies are machined, by a simple normalizing (air cooling) and tempering operation.

A hardness of about 275 to 325 Brinell is quite common in these applications and sometimes free-machining modifications of the steels are selected. For extremely long runs on the alloys of higher melting point in this general group, these steels may be heat treated to slightly higher hardnesses, up to about 450 Brinell.

Gray cast iron is used for permanent molds with these low-melting alloys.

For aluminum and magnesium alloys, heat treated alloy tool steels are required, the most popular being H11★, H12★ and H13. After machining, these steels may be hardened by air cooling with little or no distortion. They have

excellent resistance to heat checking and service failures when heat treated to Rockwell C 43 to 48.

The same alloys are satisfactory for gravity casting of copper alloys, but for maximum life H20★, H21★ or H23 should be used. Steel H23 has extremely high resistance to softening and is probably the most satisfactory steel for gravity casting of copper alloys.

Die casting of copper alloys requires special steels and heat treatment procedures, with H20★, H21★ and H23 being applicable. Modifications of these compositions have been specifically designed.

Die-casting dies used for aluminum or copper are water cooled in service and should be preheated (usually to about 350 F) before starting a run. The water cooling can be more severe and intermittent on steels H11★, H12★ and H13, but must be extremely carefully applied to H20★, H21★ and H23. Preheating should be done with water flowing slowly through the die, to prevent serious damage from the introduction of cold water into a hot die.

Nitrided Nitralloy G is employed for special applications of die-casting dies where moving parts, such as cores and slides, require added surface wear resistance. Resistance to heat checking is usually less than in steels such as H11★.

Type 410 stainless steel is utilized for permanent molds for casting a variety of nonferrous alloys.

Heat Treatment. Steel H23 is hardened by quenching from 2100 to 2350 F in oil or molten salt. It is tempered at 1200 to 1500 to Rockwell C 47 to 30. Heat treatments for the other steels mentioned are given on page 673 in the 1948 Handbook.

*Stocked in almost every warehousing district and made by the majority of tool steel producers.

The Heat Treatment of Tool Steels

A GUIDE TO THE 1948 SECTION

The heat treatment of tool steels has been largely omitted from this article because the extensive coverage on that subject in the 1948 Metals Handbook remains essentially accurate in 1954.

The 1948 Handbook section on tool steels begins on page 653 with a general discussion of heat treating and forging of tool steels, which includes a table (page 657) of forging, normalizing and annealing instructions for the 56 principal types of steel considered in the 1948 edition.

Following that summary table, the 1948 section discusses, in separate articles, the heat treatment of three major classes of tool steel:

Carbon tool steel
"Nondeforming" tool steel
Shock-resisting tool steel.

The remainder of the 1948 section consists of ten articles on the heat treatment of specific tools:

High speed steel cutting tools
Die blocks and hot die inserts
Hot forging machine tools
Hot and cold trimming tools
Solid shear blades
Press tools for cold shearing, blanking, punching, forming and coining

Cold heading dies
Thread-rolling dies
Die-casting dies and permanent molds
Plastic molds

Working hardnesses for these ten types of tools are given; also, detailed information on preheating, hardening, and tempering to produce that optimum hardness in the particular tool is tabulated in each article.

Additional information on heat treatment of tool steels is presented elsewhere in the 1948 book: An extensive discussion on the heat treatment of high speed steel tools in molten salt appears on pages 286 to 288; hardenability testing of tool steels and other tests relating to hardening are discussed on pages 418 and 419, in the article on Physical and Mechanical Testing of Tool Steels.

Heat treating information has been included in this Supplement for the following items: gages (page 31), tools for hot extrusion (page 26), and tools for cold drawing (page 27)—none of which were included in the 1948 Metals Handbook.

Stainless Steels

By the ASM Committee on Stainless Steel

THIS ARTICLE supersedes the one on pages 553 to 556 of the 1948 ASM Metals Handbook and supplements the other five articles on stainless or corrosion-resistant alloys in that same section.

Wrought Alloys

Production exceeded one million net tons of ingots for the first time in 1953. Trends during the past 20 years for total stainless steel ingots and for various groups and individual types are shown in Fig. 1.

For several years the straight-chromium type 430 (17% Cr) has been the leader on a tonnage basis, and in 1953 its production was 96% as great as that of all the austenitic types combined. This high production was caused largely by the demands of the automotive industry. In addition, it was influenced by a period of nickel shortage when the austenitic types were restricted to more critical applications.

Austenitic Stainless Steels contain chromium and nickel in proportions that usually result in a single phase, austenite. Composition limits of the standard AISI steels are given in Table I; mechanical properties of the an-

nealed steels, in Table II. General characteristics and uses are as follows:

Type 301 has the lowest nickel content of the austenitic types. Low nickel results in high strength after cold working. The steel is used in light-weight high-strength construction; structural members are cold fabricated from $\frac{1}{4}$ -hard or $\frac{1}{2}$ -hard sheet and strip; cold working during fabrication further increases strength and hardness. Type 301 is also used in the soft condition in automotive and architectural trim. Table III shows the properties developed in types 301 and 302 strip by various amounts of cold rolling. Other austenitic types can be cold rolled to increase the strength but only 301 and 302 are widely used in that condition—for example, for railroad passenger coaches, truck trailers and aircraft parts. These two steels may be welded if not subject to severe corrosive service.

Type 302 has higher nickel, which makes the austenite more stable than in type 301; it work hardens at a lower rate to lower strength properties. This permits more severe forming during fabrication. Type 302 is used in food processing, dairy and kitchen equipment, flatware and architecture, as well as in light-weight structures.

The 302B modification has 2 to 3% Si to increase oxidation resistance at elevated temperature.

Type 303 is the free-machining austenitic steel. Machinability is improved by phosphorus, sulfur or selenium; zirconium or molybdenum is sometimes added also. It is available as rod and wire for high-production screw-machine work and cold heading.

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Table I. Composition Limits of Wrought Stainless and Heat-Resisting Steels (AISI)

AISI Type	Composition, %					
	C	Mn (max)	Si (max)	Cr	Ni	Other ^(a)
Austenitic Steels						
301	0.08 to 0.20	2.00	1.00	16.00 to 18.00	6.00 to 8.00	...
302	0.08 to 0.20	2.00	1.00	17.00 to 19.00	8.00 to 10.00	...
302B	0.08 to 0.20	2.00	2.00 to 3.00	17.00 to 19.00	8.00 to 10.00	...
303	0.15 max	2.00	1.00	17.00 to 19.00	8.00 to 10.00	(b)
304	0.08 max	2.00	1.00	18.00 to 20.00	8.00 to 11.00	...
304L	0.03 max	2.00	1.00	18.00 to 20.00	8.00 to 11.00	...
305	0.12 max	2.00	1.00	17.00 to 19.00	10.00 to 13.00	...
308	0.08 max	2.00	1.00	19.00 to 21.00	10.00 to 12.00	...
309	0.20 max	2.00	1.00	22.00 to 24.00	12.00 to 15.00	...
309S	0.08 max	2.00	1.00	22.00 to 24.00	12.00 to 15.00	...
310	0.25 max	2.00	1.50	24.00 to 26.00	19.00 to 22.00	...
310S	0.08 max	2.00	1.50	24.00 to 26.00	19.00 to 22.00	...
314	0.25 max	2.00	1.50 to 3.00	23.00 to 26.00	19.00 to 22.00	...
316	0.10 max	2.00	1.00	16.00 to 18.00	10.00 to 14.00	Mo 2.00 to 3.00
316L	0.03 max	2.00	1.00	16.00 to 18.00	10.00 to 14.00	Mo 1.75 to 2.50
317	0.10 max	2.00	1.00	18.00 to 20.00	11.00 to 14.00	Mo 3.00 to 4.00
321	0.08 max	2.00	1.00	17.00 to 19.00	8.00 to 11.00	Ti 5 x C min
347	0.08 max	2.00	1.00	17.00 to 19.00	9.00 to 12.00	Cb 10 x C min
Martensitic Steels						
403	0.15 max	1.00	0.50	11.50 to 13.00	...	...
410	0.15 max	1.00	1.00	11.50 to 13.50	...	...
416	0.15 max	1.25	1.00	12.00 to 14.00	...	(c)
420	0.15 min	1.00	1.00	12.00 to 14.00	...	...
431	0.20 max	1.00	1.00	15.00 to 17.00	1.25 to 2.50	...
440A	0.60 to 0.75	1.00	1.00	16.00 to 18.00	...	Mo 0.75 max
440B	0.75 to 0.95	1.00	1.00	16.00 to 18.00	...	Mo 0.75 max
440C	0.95 to 1.20	1.00	1.00	16.00 to 18.00	...	Mo 0.75 max
501	0.10 min	1.00	1.00	4.00 to 6.00	...	...
502	0.10 max	1.00	1.00	4.00 to 6.00	...	...
Ferritic Steels						
405	0.08 max	1.00	1.00	11.50 to 13.50	...	Al 0.10 to 0.30
430	0.12 max	1.00	1.00	14.00 to 18.00	...	...
430F	0.12 max	1.25	1.00	14.00 to 18.00	...	(c)
446	0.35 max	1.50	1.00	23.00 to 27.00	...	N 0.25 max

(a) Other elements are as follows:

(b) **Austenitic Steels.** Phosphorus is 0.045% max and sulfur is 0.030% max, except for type 303, in which phosphorus or sulfur or selenium is 0.07% min, with zirconium or molybdenum 0.60% max.

(c) **Martensitic Steels.** Phosphorus is 0.040% max and sulfur is 0.030% max, except for types 416 and 430F, in which phosphorus or selenium is 0.07% min, with zirconium or molybdenum 0.60% max. Type 441 has been omitted from this article because of lack of extensive use.

Type 303 should not be welded if strength and toughness are required of the welds.

Type 304 is used in chemical equipment requiring welded fabrication. The steel has lower carbon than 301 and 302, making welding less of a hazard to corrosion resistance at the joints. However, heating between 800 and 1500°F (as in welding or stress relieving) makes the steel susceptible to intergranular attack in the heated areas when subsequently exposed to strongly corrosive mediums. Type 304 resists oxidizing mediums better than reducing mediums, as the latter tend to destroy surface passivity. The 304L modification has carbon limited to 0.03%. Lowering the carbon to this level renders the steel virtually immune to intergranular corrosion, for service below 800°F, after welding or stress relieving.

Type 305 has higher nickel than 302, which provides a low rate of work hardening favorable to severe cold forming such as spinning.

Type 308, similar to 305 but lower in carbon, is used as welding rods for 301, 302, 304 and several of the ferritic and martensitic stainless steels.

Type 309 contains more chromium and nickel (23-13) than the foregoing types (17-7 to 20-11) and has greater

Supersedes the article on pages 553 to 556 of the 1948 ASM Metals Handbook and supplements the rest of that section

Table II. Nominal Mechanical Properties of Wrought Stainless and Heat-Resisting Steels in the Annealed Condition (AISI)

AISI Type	Tensile Strength, psi	0.2% Yield Strength, psi	Elongation in 2 in., %
Austenitic Steels^(a)			
301	105,000	40,000	55
302	90,000	35,000	60
302B	90,000	40,000	50
303	90,000	35,000	50
304	85,000	30,000	60
304L	75,000	28,000	50
305	85,000	35,000	55
308	85,000	30,000	55
309 ^(b)	95,000	40,000	45
310 ^(b)	95,000	45,000	50
314	100,000	50,000	45
316	85,000	35,000	55
316L	75,000	32,000	50
317	85,000	40,000	50
321	85,000	30,000	55
347	90,000	35,000	50
Martensitic Steels^(c)			
403	75,000	40,000	35
410	70,000	35,000	30
416	75,000	40,000	30
420	95,000	50,000	25
431	125,000	95,000	20
440A	105,000	60,000	20
440B	107,000	62,000	18
440C	110,000	65,000	14
501	70,000	30,000	28
502	65,000	25,000	30
Ferritic Steels^(d)			
405	65,000	40,000	30
430	75,000	40,000	30
430F	80,000	55,000	25
446	85,000	55,000	25

(a) All of the austenitic steels have Izod impact strength from 80 to 120 ft-lb, reduction of area 50 to 70%, Brinell hardness 135 to 180, Rockwell B 70 to 90.

(b) Types 309S and 310S have properties similar to 309 and 310.

(c) For data on reduction of area, hardness and Izod impact strength of the martensitic steels, see Table V.

(d) With the exception of type 405, the annealed ferritic steels do not have high impact strength. Brinell hardness is from 135 to 175, Rockwell B 70 to 90.

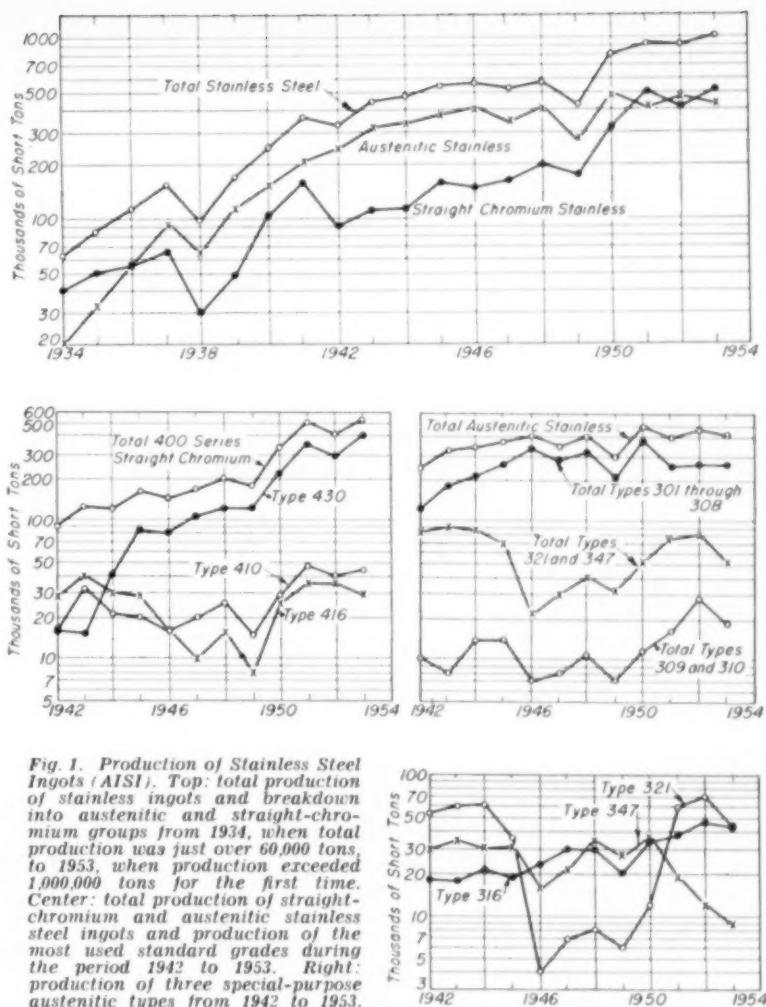


Fig. 1. Production of Stainless Steel Ingots (AISI). Top: total production of stainless ingots and breakdown into austenitic and straight-chromium groups from 1934, when total production was just over 60,000 tons, to 1953, when production exceeded 1,000,000 tons for the first time. Center: total production of straight-chromium and austenitic stainless steel ingots and production of the most used standard grades during the period 1942 to 1953. Right: production of three special-purpose austenitic types from 1942 to 1953.

Table III. Effect of Cold Rolling on Types 301 and 302 Austenitic Stainless Steels^(a)

Cold Reduction, %	Condition of Metal	Direction to Rolling	Yield Strength, ^(b) psi	Tension			Rockwell Hardness Number	Compression	
				Tensile Strength, psi	Elongation in 2 in., %	Rockwell Hardness Number		Yield Strength, ^(b) psi	Buckling Strength, psi
Type 301 Stainless Steel									
0	Annealed	Longitudinal	33,000	117,500	68	B 85	40,000	57,800	
0	Annealed	Transverse	33,000	113,500	62		44,000	57,400	
10	Cold rolled	Longitudinal	67,000	147,600	47	C 32	54,000	89,400	
10	Cold rolled	Transverse	72,000	147,100	36		81,000	97,700	
25	Cold rolled	Longitudinal	127,000	165,200	24	C 38	96,000	151,400	
25	Cold rolled	Transverse	124,000	170,500	17		143,000	172,200	
35	Cold rolled	Longitudinal	164,000	196,000	15	C 43	139,000	184,500	
35	Cold rolled	Transverse	138,000	201,000	10		185,000	214,300	
45	Cold rolled	Longitudinal	200,000	225,000	7	C 46	163,000	218,000	
45	Cold rolled	Transverse	176,000	234,000	7		230,000	250,000	
Type 302 Stainless Steel									
0	Annealed	Longitudinal	36,000	94,000	61	B 90	36,000	50,250	
0	Annealed	Transverse	34,000	93,700	61		36,000	50,000	
20	Cold rolled	Longitudinal	121,000	139,300	22	C 29	74,000	120,400	
20	Cold rolled	Transverse	113,000	138,500	17		121,000	145,000	
35	Cold rolled	Longitudinal	131,000	155,300	15	C 36	95,000	151,800	
35	Cold rolled	Transverse	130,000	166,200	11		148,000	183,110	
50	Cold rolled	Longitudinal	151,000	177,400	6	C 38	99,000	155,200	
50	Cold rolled	Transverse	147,000	189,200	8		166,000	166,700	

(a) Data are the results of specific individual tests on strip 0.035 in. thick, as reported by Russell Franks and W. O. Binder, J Aeronautical Sci, Sept 1942.

(b) 0.2% offset. In testing, sufficient time was allowed after the application of each increment of load to permit the strain to be measured accurately.

Table IV. Physical Properties and Working Characteristics of Wrought

Property	301	302	302B	303	304	305	308
Modulus of elasticity in tension, psi...	28,000,000 ^(a)	28,000,000 ^(b)	28,000,000	28,000,000	28,000,000	28,000,000	28,000,000
Modulus of elasticity in torsion, psi...	12,500,000 ^(b)	12,500,000 ^(b)	...	...	12,500,000	12,500,000	...
Density.....{ lb per cu in.....	0.29	0.29	0.29	0.29	0.29	0.29	0.29
{ g per cu cm.....	7.9	7.9	7.9	7.9	7.9	7.9	7.9
Specific electrical resistance at room temperature, microhm-cm.....	72	72	72	72	72	72	72
Magnetic permeability { Annealed.....	...	1.003	...	1.003	1.02	...	...
{ 10% cold worked.....	...	1.10	...	...	1.10	...	...
{ Severely cold worked.....	...	10.0	...	...	7.0	...	...
Specific heat, Btu/lb deg Fahr (32 to 212 F).....	0.12	0.12	0.12	0.12	0.12	0.12	0.12
{ 212 F.....	9.4	9.4	9.2	9.4	9.4	9.4	8.8
Thermal conductivity, Btu/hr/sq ft/ft/deg Fahr	392 F.....	10.2	...	...	10.3	...	...
572 F.....	10.9	...	...	11.0	...	...	...
752 F.....	11.6	...	...	11.8	...	...	...
932 F.....	12.4	12.4	12.5	12.4	12.5	12.4	12.5
{ 32 to 212 F.....	0.0000094	0.0000096	0.0000090	0.0000096	0.0000096	0.0000096	0.0000096
{ 32 to 572 F.....	0.0000095	0.0000099	0.0000100	0.0000099	0.0000099	0.0000099	0.0000099
Mean coefficient of thermal expansion per deg Fahr.....	32 to 932 F (AISI, 600 F).....	0.0000101	0.0000102	0.0000108	0.0000102	0.0000102	0.0000102
{ 32 to 1112 F (AISI, 1200 F).....	0.0000104	0.0000104	0.0000112	0.0000104	0.0000104	0.0000104	0.0000104
{ 32 to 1832 F (AISI, 1800 F).....	...	0.0000112	...	...	0.0000112	...	...
Maximum temperature without excessive scaling, deg Fahr.....	...	1650	...	1600	1650	...	...
Melting range, deg Fahr.....	2550 to 2590	2550 to 2590	2500 to 2550	2550 to 2590	2550 to 2650	2550 to 2650	2550 to 2590
Forging practice { Initial temperature, deg Fahr.....	2100 to 2300	2100 to 2300	2050 to 2250	2100 to 2350	2100 to 2300	2100 to 2300	2100 to 2300
{ Final temperature, deg Fahr.....	1700 to 1750	1700 to 1750	...	1700 to 1750	1650 to 1700	...	...
Annealing temperature, deg Fahr.....	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050	Cool rapidly from 1850 to 2050
Low anneal.....	...	...	...	...	...	...	...
Full anneal.....	...	...	...	...	...	...	...
Maximum cold reduction of wire before anneal, %.....	80	80	...	50	80	...	...
Riveting and hot forming temperatures, deg Fahr.....	...	1900 to 2100	...	...	1900 to 2100	...	...
Stress relieving, deg Fahr.....	400 to 750	400 to 750	400 to 750	400 to 750	400 to 750	400 to 750	400 to 750
Property	501	502	403	405	410	416	420
Modulus of elasticity in tension, psi...	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000
Modulus of elasticity in torsion, psi...	...	...	...	...	...	...	11,700,000
Density.....{ lb per cu in.....	0.28	0.28	0.28	0.28	0.28	0.28	0.28
{ g per cu cm.....	7.8	7.8	7.8	7.7	7.7	7.7	7.7
Specific electrical resistance at room temperature, microhm-cm.....	40	40	57	60	57	57	55
Magnetic permeability	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic
Specific heat, Btu/lb/deg Fahr (32 to 212 F).....	0.11	0.11	0.11	0.11	0.11	0.11	0.11
{ 212 F.....	21.2	21.2	14.4	...	14.4	14.4	14.4
Thermal conductivity, Btu/hr/sq ft/ft/deg Fahr	392 F.....	20.8	...	...	15.0	...	...
572 F.....	20.4	...	...	...	15.5	...	...
752 F.....	19.8	...	...	...	16.1	...	...
932 F.....	19.5	19.5	16.6	...	...	16.6	...
Mean coefficient of thermal expansion { 32 to 212 F.....	0.0000062	0.0000062	0.0000055	0.0000060	0.0000061	0.0000055	0.0000057
{ 32 to 600 F.....	0.0000068	0.0000068	0.0000056	0.0000064	...	0.0000056	...
{ 32 to 1000 F.....	0.0000072	0.0000072	0.0000064	0.0000067	0.0000072	0.0000064	...
{ 32 to 1200 F.....	0.0000073	0.0000073	0.0000065	0.0000075	...	0.0000065	0.0000068
{ 32 to 1832 F.....	...	...	...	...	0.0000076	...	0.0000076
Maximum temperature without excessive scaling, deg Fahr.....	...	1150	...	...	1250	...	1200
Melting range, deg Fahr.....	2700 to 2800	2700 to 2800	2700 to 2790	2700 to 2790	2700 to 2790	2700 to 2790	...
Forging practice { Initial temperature, deg Fahr.....	2100 to 2200	2100 to 2200	2000 to 2200	1950 to 2050	2000 to 2150	2100 to 2300	2000 to 2150
{ Final temperature, deg Fahr.....	...	1500 to 1600	...	...	1400 to 1500	...	1700 to 1750
Method of cooling	Retarded cool Cool from 1325 to 1375	Slow cool Cool from 1325 to 1375	Retarded cool 1350 to 1500	...	Slow cool Air cool from 1200 to 1350	Retarded cool 1200 to 1400	Slow cool from 1250 to 1650
Annealing temperatures, deg Fahr.....	Low anneal { Cool from 1325 to 1375	Slow cool from 1525 to 1600	Slow cool from 1500 to 1650	...	Slow cool from 1500 to 1600	Slow cool from 1500 to 1650	Rapid cool from 1850 to 1900
{ Full anneal { 1525 to 1600	1600	1600	1650	...	1800	1850	...
Hardening temperature, deg Fahr ...	Rapid cool from 1600 to 1700	Rapid cool from 1600 to 1700	Rapid cool from 1700 to 1850	Not appreciably hardenable	Rapid cool from 1750 to 1800	Rapid cool from 1700 to 1850	...
Maximum cold reduction of wire before anneal, %.....	...	75	...	...	75	...	...
Riveting and hot forming temperatures, deg Fahr.....	...	Below 1450	...	...	Below 1450	...	...

(a) Type 301 is used in the cold-worked condition for lightweight high-strength structures. As cold worked, the modulus in tension is lowered. By stress-relief treatment this value may be

raised to 27,500,000 psi. (b) As cold worked, this value decreases Data from ASTM Special Technical Publication 52-A (1950)

Stainless and Heat-Resisting Steels in the Annealed Condition (ASTM)

Property	309	310	314	316	317	321	347
Modulus of elasticity in tension, psi...	29,000,000	30,000,000	29,000,000	28,000,000	28,000,000	28,000,000	28,000,000
Modulus of elasticity in torsion, psi...	....	....	....	....	....	....	....
Density.....{ lb per cu in.	0.29	0.29	0.279	0.29	0.29	0.29	0.29
g per cu cm	7.9	7.9	....	8.0	....	7.9	8.0
Specific electrical resistance at room temperature, microhm-cm	78	78	77	74	74	72	73
Magnetic permeability { Annealed	1.003	1.003	....	1.003	....	1.02	1.02
10% cold worked .....	....	....	....	....	....	....	....
Severely cold worked .....	....	....	....	10.0	....	....	....
Specific heat, Btu/lb deg Fahr (32 to 212 F)	0.12	0.12	0.12	0.12	0.12	0.12	0.12
212 F,	8.0	7.5	10.1	9.0	9.4	9.3	9.3
392 F, ....	....	8.2	....	....	....	10.2	10.2
572 F, ....	....	8.8	....	....	....	11.1	11.1
752 F, ....	....	9.5	....	....	....	11.9	11.9
932 F,	10.8	10.0	12.1	12.1	12.4	12.8	12.8
32 to 212 F,	0.0000083	0.0000080	....	0.0000089	0.0000089	0.0000093	0.0000093
32 to 572 F, (AISI, 600 F)	0.0000093	0.0000090	0.0000084	0.0000090	0.0000090	0.0000095	0.0000095
32 to 932 F, (AISI, 1000 F)	0.0000096	0.0000094	....	0.0000097	0.0000097	0.0000103	0.0000103
32 to 1112 F, (AISI, 1200 F)	0.0000100	0.0000097	....	0.0000103	0.0000103	0.0000107	0.0000106
32 to 1500 F, ....	....	....	0.0000098	0.0000111	0.0000111	0.0000112	0.0000111
32 to 1832 F, (AISI, 1800 F)	0.0000115	0.0000106	....	....	....	....	....
Maximum temperature without excessive scaling, deg Fahr	2000	2000	....	1650	....	1650	1650
Melting range, deg Fahr	2550 to 2650	2550 to 2650	....	2500 to 2550	2500 to 2550	2550 to 2600	2550 to 2600
Forging practice { Initial temperature, deg Fahr	2050 to 2250	2000 to 2250	1900 to 2050	2100 to 2300	2100 to 2300	2100 to 2300	2100 to 2300
Final temperature, deg Fahr	1800 to 1850	1800 to 1850	....	1700 to 1750	....	1650 to 1700	1700 to 1750
Annealing temperature, deg Fahr	1800 to 1850 from 1900 to 2050	Cool rapidly from 1900 to 2100	Cool rapidly from 2100	1700 to 1750 from 1850 to 2050	Cool rapidly from 1850 to 2050	....	....
Low anneal .....	....	....	....	....	....	1550 to 1650	1550 to 1650
Full anneal .....	....	....	....	....	....	1750 to 1950	1850 to 2050
Maximum cold reduction of wire before anneal, %	80	80	....	80	....	80	80
Riveting and hot forming temperatures, deg Fahr	1900 to 2100	1900 to 2100	....	1900 to 2100	....	1900 to 2100	1900 to 2100
Stress relieving, deg Fahr	400 to 750	400 to 750	....	400 to 750	400 to 750	400 to 750	400 to 750
Property	430	430F	431	440A	440B	440C	446
Modulus of elasticity in tension, psi...	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000	29,000,000
Modulus of elasticity in torsion, psi...	....	....	....	....	....	....	....
Density.....{ lb per cu in.	0.28	0.28	0.28	0.28	0.28	0.28	0.27
g per cu cm	7.7	....	....	....	....	....	7.6
Specific electrical resistance at room temperature, microhm-cm	60	60	72	60	60	60	67
Magnetic permeability { Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic	Ferro-magnetic
Specific heat, Btu/lb deg Fahr (32 to 212 F)	0.11	0.11	0.11	0.11	0.11	0.11	0.12
212 F,	15.1	15.1	11.7	14.0	14.0	14.0	12.1
392 F,	15.2	....	....	....	....	....	12.7
572 F,	15.2	....	....	....	....	....	13.3
752 F,	15.2	....	....	....	....	....	13.8
932 F,	15.2	15.2	....	....	....	....	14.1
32 to 212 F, 0.0000058	0.0000058	0.0000058	0.0000065	0.0000056	0.0000056	0.0000056	0.0000059
32 to 600 F, 0.0000061	0.0000061	0.0000061	0.0000067	....	....	....	....
32 to 1000 F, 0.0000063	0.0000063	....	....	....	....	....	0.0000063
32 to 1200 F, 0.0000066	....	....	....	....	....	....	....
32 to 1832 F, 0.0000073	0.0000069	....	....	....	....	....	0.0000076
Maximum temperature without excessive scaling, deg Fahr	1550	....	....	....	....	....	2000
Melting range, deg Fahr	2700 to 2750	2600 to 2750	....	2500 to 2750	2500 to 2750	2500 to 2700	2700 to 2750
Forging practice { Initial temperature, deg Fahr	1900 to 2050	1950 to 2100	2100 to 2250	1900 to 2200	1900 to 2150	1900 to 2100	1900 to 2000
Final temperature, deg Fahr	1300 to 1500	....	Retarded cool	Retarded cool	Retarded cool	Retarded cool	1300 to 1450
Method of cooling .	Air cool	1250 to 1400	1150 to 1225	Impractical	1350 to 1450	1350 to 1450	Air cool
Annealing tempera-tures, deg Fahr	Low anneal	....	....	Slow cool from 1550 to 1650	Slow cool from 1550 to 1650	Slow cool from 1550 to 1650	Rapid cool from 1450 to 1550
Full anneal	....	....	....	....	....	....	....
Hardening tempera-ture, deg Fahr ...	Non-hardening	Not appreciably hardenable	Rapid cool from 1850 to 1950	Rapid cool from 1850 to 1950	Rapid cool from 1850 to 1950	Rapid cool from 1850 to 1950	Non-hardening
Maximum cold reduction of wire before anneal, %	75	....	....	....	....	....	75
Riveting and hot forming temperatures, deg Fahr	Below 1450	....	....	....	....	....	Below 1650

(a) From 32 to 1500 F. Data from ASTM Special Technical Publication 52-A (1950).

Stainless Steels

oxidation resistance at high temperature. Type 309S has lower carbon than 309, reducing the degree of carbide precipitation at elevated temperature.

Type 310 has higher nickel than 309, which, with the 1½% max Si, increases both oxidation resistance and strength at elevated temperature. Modification 310S has lower carbon, reducing the degree of carbide precipitation.

Type 314 has greater oxidation resistance than 310 as a result of increased silicon content; the structure is less stable, however.

Type 316 steel has the best corrosion resistance of the 18-8 types in highly ionized reducing acids, as a result of its molybdenum content. Type 316 is used at elevated temperatures, as well as for handling liquids in chemical and processing industries. The lower-carbon modification, 316L, is essentially immune to intergranular attack due to precipitation of chromium carbide during welding or stress relieving, in strongly corrosive uses below 800 F.

Type 317 has higher alloy content than 316 for applications requiring increased corrosion resistance.

Type 321 is the 18-8 analysis with titanium added to make the steel virtually free from intergranular attack in corrosive mediums up to 1500 F after welding or stress relieving. It is used in high-temperature service, principally in and around aircraft engines.

It is also used to some extent in the chemical and processing industries.

In type 347 similar immunity to intergranular corrosion is provided by the addition of columbium. As with 321 the immunity persists to about 1500 F, which is about the limiting scaling temperature. The material is used in strongly corrosive applications and also in high-temperature aircraft and steam power service. Types 321 and 347 are often interchangeable (see Metal Progress, Nov 1950, p 691).

Physical properties and working characteristics of the annealed austenitic steels are given in Table IV.

Martensitic Stainless Steels contain between 11.5 and 18% Cr. They can be hardened by quenching. Composition limits of the standard grades are given in Table I and mechanical properties in the annealed condition in Table II. Mechanical properties of the steels after hardening and tempering are listed in Table V.

Type 403 is widely used for forged or machined turbine and compressor blades and other highly stressed parts. Type 410 is used in the heat treated condition in valve stems and pump linings, and as annealed sheet and strip for lining oil-refinery vessels and in mining equipment where abrasion resistance is required along with corrosion resistance.

Type 416, the free-machining grade of type 410, is available as bar and wire for high-production screw-machine work. It should not be welded if strength or toughness is required.

Type 420 has higher carbon to provide greater hardness in the heat treated condition. It is principally used for cutlery, valve parts and corrosion-resistant ball bearings.

Type 431, containing 2% Ni, has increased corrosion resistance and about the same strength as the nickel-free martensitic steels.

Types 440A, 440B and 440C are cutlery compositions of increasing carbon content and hardenability. These steels are used for surgical instruments, cutlery, anti-friction bearings, valves and other applications requiring high hardness and good corrosion resistance where toughness is not important.

Types 501 and 502, containing 5% Cr and 0.50% Mo, resist mildly corrosive conditions but are not "stainless". They are used in the oil-refining industry as still tubes, where a combination of high creep strength and some corrosion resistance is required. Type 502 has lower carbon with correspondingly lower hardening characteristics and better weldability.

Physical properties and fabrication characteristics of the martensitic stainless steels are given in Table IV.

Ferritic Stainless Steels are not usefully hardenable by heat treatment. Compositions are given in Table I and mechanical properties in the annealed condition in Table II.

Type 405 is the 410 composition with a small amount of aluminum added to inhibit air hardening from welding or brazing.

Type 430, the stainless steel with

Table V. Nominal Mechanical Properties of Wrought Martensitic Stainless Steels^(a)

AISI Type	Tempering Temperature, deg Fahr. ^(b)	Tensile Strength, psi	0.2% Yield Strength, psi	Elongation in 2 in., %	Reduction of Area, %	Izod Impact ft-lb	Hardness	
							Brinell	Rockwell
403	Annealed	75,000	40,000	35	70	90	155	B 82
410	Annealed	70,000	35,000	30	..	70	150	...
403 and 410	Quenched	...	...	..	..	..	410	C 43
410	400	190,000	145,000	15	55	35	390	C 41
	600	180,000	140,000	15	55	35	375	C 39
	800 ^(c)	195,000	150,000	17	55	..	390	C 41
	1000 ^(c)	145,000	115,000	20	65	..	300	C 31
	1200	110,000	85,000	23	65	75	225	B 97
	1400	90,000	60,000	30	70	100	180	B 89
416	Annealed	75,000	40,000	30	60	30	155	B 82
	Quenched	...	...	..	..	..	410	C 43
	400	190,000	145,000	12	45	20	390	C 41
	600	180,000	140,000	13	45	20	375	C 39
	800 ^(c)	195,000	150,000	13	50	..	390	C 41
	1000 ^(c)	145,000	115,000	15	50	..	300	C 31
	1200	110,000	85,000	18	55	30	225	B 97
	1400	90,000	60,000	25	60	60	180	B 89
431	Annealed	125,000	95,000	20	55	50	260	C 24
	Quenched	...	...	..	..	..	440	C 45
	400 [*]	205,000	155,000	15	55	30	415	C 43
	600	195,000	150,000	15	55	45	400	C 41
	800 ^(c)	205,000	155,000	15	60	..	415	C 43
	1000 ^(c)	150,000	130,000	18	60	..	325	C 34
	1200	125,000	95,000	20	60	50	260	C 24
420	Annealed	95,000	50,000	25	55	..	195	B 92
	Quenched	...	...	..	..	10	540	C 54
	600	230,000	195,000	8	25	..	500	C 50
440A	Annealed	105,000	60,000	20	45	2	215	B 95
	Quenched	...	...	..	..	..	570	C 56
	600	260,000	240,000	5	20	4	510	C 51
440B	Annealed	107,000	62,000	18	35	2	220	B 96
	Quenched	...	...	..	..	..	590	C 58
	600	280,000	270,000	3	15	3	555	C 55
440C	Annealed	110,000	65,000	14	25	2	230	B 97
	Quenched	...	...	..	..	..	610	C 60
	600	285,000	275,000	2	10	2	590	C 57

(a) Data for bars 1 in. in diameter, AISI Steel Products Manual, Section 24, April 1950.

(b) Quenching temperatures: 403, 410 and 416, 1800 F; others, 1900 F

(c) Tempering within the range from 750 to 1050 F is not recommended because of low and erratic impact properties

highest volume of production, is used mostly in automotive trim. It is also widely used architecturally and in certain specific chemical applications. Type 430 is not so easily formed as 18-8 in applications involving severe bending or extra deep drawing. Type 430F is the free-machining ferritic steel.

Type 446 has 25% Cr for increased resistance to oxidation at elevated temperatures.

Physical properties and working characteristics of the ferritic stainless steels are listed in Table IV.

Corrosion Resistance. The article on pages 557 to 561 of the 1948 Handbook gives detailed information on the corrosion resistance of the wrought stainless steels and the effects of heat treatment and other variables on corrosion behavior. The curve on page 562 in that article indicates the important effect of chromium content on oxidation resistance. Figure 2 here shows the relative resistance of commercial steels to scaling, measured by gain in weight in 1000 hr.

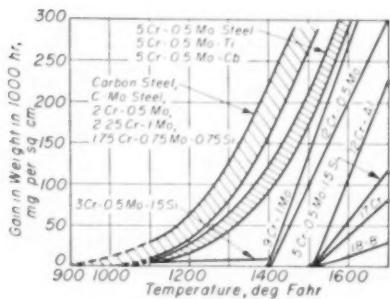


Fig. 2. Scaling of Stainless and Other Steels in Air

Welding. The austenitic stainless steels can be satisfactorily welded by all production methods. The steels are equally weldable in the annealed and cold rolled conditions. The ratio of impact strength to tensile strength in resistance welds is higher than in any other alloys commonly used for structural purposes. Although areas of stress concentration will develop in spot welds, joints can be designed to withstand heavy fatigue loads. The austenitic steels have a coefficient of thermal expansion about 60% greater than mild steel; this must be considered in joining, to minimize warping or distortion of the part.

Recommendations are given in Table VI regarding electrodes and post-weld heat treatments.

The one serious difficulty that can be encountered in welding these steels is intergranular corrosion of the metal in or alongside the weld. When the unstabilized 18-8 steels are heated within the range 800 to 1500 F, either locally as in welding or completely as in stress relieving, precipitation of chromium carbide occurs at the grain boundaries in the reheated metal, and on subsequent exposure to corroding conditions the steels may be attacked at the grain boundaries. This difficulty can be overcome by heat treating the welded structure at temperatures high enough to redissolve the carbide, by adding a strong carbide-forming element (co-

Table VI. Recommended Heat Treatments and Electrodes for Welding Wrought Austenitic, Ferritic and Martensitic Stainless Steels

AISI Type	Pre-Weld	Recommended Heat Treatment		Recommended Electrode
			Post-Weld	
Austenitic Steels				
301	(a)	Cool rapidly from between 1950 and 2100 F if corrosion conditions are moderate to severe.		308
302	(a)	Cool rapidly from between 1850 and 2000 F only when corrosion conditions are strong.		308
304	(a)	Not required for corrosion resistance.	308L ^(b) or 347	308
309 ^(c)	(a)	Usually unnecessary because steel is generally in service at high temperatures.		309
310 ^(d)	(a)	Cool rapidly from between 1950 and 2100 F only when corrosion conditions are severe.		310
316	(a)	Not required for corrosion resistance.	316L	316
316L	(a)	Cool rapidly from between 1950 and 2100 F only when corrosion conditions are severe.	316L	317
321, 347	(a)	Not required for corrosion resistance.		347
Ferritic and Martensitic Steels				
403, 405	150 to 300 ^(e)	Air cool from between 1200 and 1400 F.		410
410	150 to 300 ^(e)	Air cool from between 1200 and 1350 F.		410 ^(e)
430	150 to 300 ^(e)	Air cool from between 1400 and 1450 F.		430 ^(e)
446	300 to 500	Cool rapidly from between 1550 and 1650 F.		446
501	300 to 500	Air cool from between 1325 and 1375 F.		502
502	300 to 500 ^(e)	Air cool from between 1325 and 1375 F.		502 ^(e)

(a) Unnecessary when the steel is above 60 F

(b) 0.04% C max

(c) Where corrosion is a factor, 309S and 310S are used, and post-weld heat treatment is rapid cooling from between 2000 and 2100 F

(d) Light-gage sheet is frequently welded without preheating

(e) May be welded with 308, 309 or 310 electrodes with no preheating required if steel is above 60 F

lumbium or titanium) as in types 321 and 347, or by reducing the carbon content of the 18-8 steels to a maximum of 0.03%, as in types 304L and 316L. When either of these procedures is employed the weldments are virtually immune to attack at the grain boundaries. The advantage of types 321, 347, 304L and 316L is that they can be used to resist corrosion in the as-welded or stress relieved conditions. They can be bent and formed hot during fabrication, and equipment so made can be used at moderately elevated temperatures. If operating temperatures are within the carbide precipitation range (800 to 1500 F) types 321 and 347 are preferable to 304L and 316L.

Types 309 and 310, containing higher chromium and nickel, are also weldable. Although these steels are subject to intergranular attack, their greatest usage is where intergranular corrosion is not a factor. However, when weldments are intended to resist strong chemicals, precautions must be taken to avoid the development of intergranular attack both in and adjacent to the weld. When it is necessary to improve resistance to intergranular attack in the 309 and 310 steels, the carbon content is usually decreased.

Welds in ferritic and martensitic stainless steels are not so ductile and tough as in the austenitic steels. The lower-carbon types (403, 405 and 410) are more adaptable to welding than those of higher carbon content (420 and 431). Welds in the lower-carbon steels have low ductility and toughness in the as-welded condition because they air harden. Hence, weldments must be annealed and cooled rapidly through the range 800 to 1100 F.

Types 430 and 446, containing about 17 and 25% Cr, respectively, while not significantly air hardening, are subject to grain coarsening above about 1900 F. At 2100 F the ferritic grains become very large, and ductility is decreased. Some restoration may be gained by

annealing at 1400 and 1600, respectively.

When it is necessary to join these higher-chromium steels (430 and 446) to carbon steels, austenitic stainless steel electrodes of either type 309 or 310 are recommended, particularly when the weldment cannot be postheated or stress relieved. Long exposure of these steels in the temperature range 800 to 900 F will reduce the room-temperature ductility to a very low value. This condition is especially severe in the 25% Cr steel, which also loses ductility on extended heating in the range 1300 to 1500 F because of the formation of sigma phase.

The ductility and toughness of welds in types 501 and 502 are greatly improved by annealing. The lower-carbon 502 is preferred, as it is less hardenable than the higher-carbon 501. Both grades require postheating after welding, to avoid cracking. The high-carbon martensitic types (440A, 440B and 440C) are poorly suited for welding because they air-harden easily. If they are welded, they must be preheated, slowly cooled after welding and then annealed.

Machining, Stamping and Drawing are dealt with in the article on pages 582 to 584 of the 1948 Handbook.

Castings

The physical properties, heat treatments and applications of corrosion-resistant castings given in the 1948 Handbook (pages 549 to 553) still apply. However, changes have been made in the composition ranges for some of the standard alloys; current compositions are given in Table VII and mechanical properties in Table VIII.

The production of corrosion-resistant castings has increased since 1945, as shown in Fig. 3. These cast alloys are frequently used in conjunction with wrought alloys of similar composition. Because the requirements for castability and rollability are met by different

Table VIII. Nominal Mechanical Properties of Cast Corrosion-Resistant Alloys (ACI)

Stainless Steels

balances among the constituent elements, castings should be specified by cast alloy designations, not by type numbers applying to wrought forms.

Design and Selection. Although corresponding cast and wrought alloys have equivalent corrosion resistance, the differences in physical, mechanical and fabricating characteristics should be noted carefully. For example, the cast alloy CF-8 normally shows greater ferromagnetism than the corresponding wrought alloy 304, which is virtually nonmagnetic. (Type CF-8 castings of low magnetic permeability can be made, but they should be so specified.)

Relatively few corrosion-resistant castings are used in the as-cast condition. Subsequent fabrication may be a factor in selecting alloy and design. Where limited machining is involved, any of the standard alloys may be used satisfactorily, but selenium-containing grades are recommended if extensive machining is required; the CF-16F alloy can be turned at almost twice the speed of the CF-8 type, and the chips free themselves from the tool and break more readily than with other CF grades.

Foundry difficulties that may arise in the casting of large, intricate structures often can be avoided by designing the part to be cast in two or more pieces for later fabrication by welding or bolting to make the desired unit. All of the grades can be welded satisfactorily if proper techniques are employed, as explained subsequently under Welding. Alloys CF-8C and CE-30 are useful when castings cannot be readily heat treated after welding.

Loose wood or metal patterns are subject to damage from warping and mechanical abuse, and should be considered only for large castings or when a few small or experimental parts are being made. Mounted patterns, matched patterns, or separate cope and

ACI Type	Heat Treatment ^(a)	Tensile Strength, psi	0.2% Yield Strength, psi	Elongation in 2 in., %	Briennell Hardness Number	Charpy Impact, Key-hole, ft-lb
CA-15	AC, 1800 F; temp, 1450 F ...	100,000	75,000	30	185	35
	AC, 1800 F; temp, 1200 F ...	115,000	100,000	22	225	20
	AC, 1800 F; temp, 1100 F ...	135,000	115,000	17	260	10
	AC, 1800 F; temp, 600 F ...	200,000	150,000	7	390	15
CA-40	AC, 1800 F; temp, 1400 F ...	110,000	67,000	18	212	3
	AC, 1800 F; temp, 1200 F ...	140,000	113,000	14	267	4
	AC, 1800 F; temp, 1100 F ...	150,000	125,000	10	310	2
	AC, 1800 F; temp, 600 F ...	220,000	165,000	1	470	1
CB-30	Annealed 1450 F, FC to 1000 F,					
	AC	95,000	60,000	15	195	2
CC-50	(Under 1% Ni) as cast	70,000	65,000	2	212	2 ^(b)
	(Over 2% Ni, 0.15% N min) as cast	95,000	60,000	15	193	45 ^(b)
	(Over 2% Ni, 0.15% N min) AC 1900 F	97,000	65,000	18	210	...
CE-30	As cast	95,000	60,000	15	170	...
	WC, 1950 to 2050 F	97,000	63,000	18	170	...
CF-8	WC, 1950 to 2050 F	77,000	37,000	55	140	75
	WC, 2000 F	77,000	36,000	50	163	60
CF-8M	WC, 1950 to 2100 F	80,000	42,000	50	156-170	70
	WC, 1950 to 2050 F	77,000	38,000	39	149	30
CF-16F	WC, above 2000 F	77,000	40,000	52	150	75
	WC, above 2000 F	88,000	50,000	38	190	30
CH-20	WC, 2100 F	76,000	38,000	37	144	50 ^(b)
	WC, 1950 to 2050 F	69,000	31,000	48	130	70

(a) "AC" means air cooled from temperature indicated; "temp", tempered; "FC", furnace cooled; "WC", water quenched. (b) Izod V-notch

drag patterns are essential to produce dimensionally accurate castings of high quality.

Minimum section thickness should be held to $\frac{1}{8}$ in. or greater if possible. Somewhat lighter sections are feasible for most of the alloys, depending on pattern equipment and casting design, but some difficulty is experienced in running thin sections in the straight-chromium alloys of the CA, CB and CC types. Where intricate designs are involved, the greater fluidity of austenitic chromium-nickel grades is advantageous. Designs requiring appreciable changes in section should be avoided. This applies to the casting *as cast*; that is, finish allowance of $\frac{1}{8}$ in. or more on

surfaces to be machined should be considered in the casting design.

Dimensional tolerances depend on pattern equipment and configuration. In general, over-all dimensions and location of cored holes can be held to $\frac{1}{16}$ in. per ft. Solidification shrinkage is compensated for as noted in Table IX; the figures apply only to *unhindered* contraction.

Because varying amounts of resistance to free contraction of the casting are offered by the shape of the mold, a single shrinkage allowance is necessarily a compromise. Extreme demand for dimensional accuracy may require that several different shrinkage allowances be used on a single pattern. Furthermore, an entirely different pattern may be needed to produce the same casting design if different molding methods are employed.

In addition to differences in contraction, the requirements for gates and risers vary considerably among cast iron, steel and high alloys. Pattern equipment designed for one metal

Table VII. Standard Designations and Composition Ranges for Corrosion-Resistant Castings (ACI)

ACI Designation ^(a)	Wrought Alloy Type ^(b)	Composition, %					
		C (max)	Mn (max)	Si (max)	Cr	Ni	Other ^(c)
CA-15	410	0.15	1.00	1.50	11.5 to 14	1 max	Mo 0.5 max ^(d)
CA-40	420	0.20 to 0.40	1.00	1.50	11.5 to 14	1 max	Mo 0.5 max ^(d)
CB-30	431	0.30	1.00	1.00	18 to 22	2 max	...
CC-50	446	0.50	1.00	1.00	26 to 30	4 max	...
CE-30		0.30	1.50	2.00	26 to 30	8 to 11	...
CF-8	304	0.08	1.50	2.00	18 to 21	8 to 11	...
CF-20	302	0.20	1.50	2.00	18 to 21	8 to 11	...
CF-8M	316	0.08	1.50	1.50	18 to 21	9 to 12	Mo 2.0 to 3.0
CF-12M	316	0.12	1.50	1.50	18 to 21	9 to 12	Mo 2.0 to 3.0
CF-8C	347	0.08	1.50	2.00	18 to 21	9 to 12	Cb ^(e)
CF-16F	303	0.16	1.50	2.00	18 to 21	9 to 12	Mo, Se ^(f)
CH-20	309	0.20	1.50	2.00	22 to 26	12 to 15	...
CK-20	310	0.20	1.50	2.00	23 to 27	19 to 22	...
CN-7M		0.07	1.50	(g)	18 to 22	21 to 31	Mo-Cu ^(g)

(a) Most of these standard grades are covered by ASTM A296-49T.

(b) Type numbers of wrought alloys are listed only for nominal identification of corresponding wrought and cast grades. Composition ranges of the cast alloys are not the same as for the corresponding wrought alloys; cast alloy designations should be used for castings.

(c) Phosphorus is 0.04% max except in CF-16F, which has 0.17% max; sulfur is 0.04% max in all grades.

(d) Molybdenum not intentionally added.

(e) Cb, 8xC min, 1.0% max; or Cb-Ta, 10xC min, 1.35% max.

(f) Mo, 1.5 max; Se, 0.2 to 0.35%.

(g) Several proprietary alloy compositions fall within the stated chromium and nickel ranges and contain varying amounts of silicon, molybdenum and copper.

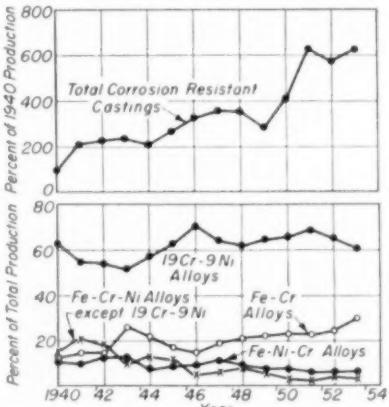


Fig. 3. Production of Corrosion-Resistant Castings (ACI)

Table IX. Patternmakers' Shrinkage for Cast Corrosion-Resistant Alloys^(a)

ACI Type	Shrinkage Allowance, in. per ft
CC-50	$\frac{1}{16}$
CA-15, CA-40, CB-30	$\frac{1}{16}$
CE-30, CF-8, CF-8M	$\frac{1}{16}$
CF-12M, CF-16F	$\frac{1}{8}$
CH-20, CK-20, CN-7M	$\frac{1}{16}$
CF-8C, CF-20	$\frac{1}{16}$

(a) These values are for unhindered contraction; considerable variation may occur, depending on the shape of the casting.

should be used for another only after consultation with the foundry producing the casting. Best results are usually obtained when the foundryman is consulted in the early stages of design.

Welding. Corrosion-resistant castings are customarily welded by the manual metal-arc method using direct current with reversed polarity (electrode positive). Certain precautions are necessary for the straight-chromium grades; lime-coated electrodes are generally used, and the rod should be the same type composition as the casting. Electrodes that contain nickel should be avoided because they will cause hard spots that cannot be eliminated by heat treatment. Pre-weld heating of castings is recommended.

Preparation of the chromium-nickel steels for welding is less involved; pre-heating is seldom required. Welds have the same chemical, physical and mechanical properties as the base metal if equivalent alloy electrodes are employed and if the castings are properly heat treated after welding. If the post-weld heat treatment is omitted, most grades will lose corrosion resistance in the weld zone. Because many of the alloys are partially ferritic they are somewhat less susceptible to intergranular attack than the corresponding grades of wrought steels which are fully austenitic. Thus fast cooling, thin sections of CF-8 and CF-8M castings can often be welded without subsequent heat treatment and still provide satisfactory corrosion resistance. The high chromium content and strongly ferritic structure of the CE-30 alloy permit welding of somewhat heavier sections without post-weld heating but where casting thickness is great enough to result in slow post-weld cooling through the range 1600 to 800 F, stabilized castings of the CF-8C type should be used or the castings should be quenched annealed as pointed out in Table X.

The recommended electrical settings for welding the cast alloys are given in Table XI. Pre-weld and post-weld heat treatments required for all the grades are listed in Table X, together with recommended electrodes.

Machining. All the cast chromium and chromium-nickel alloys are machinable with speeds about 45% of those used for Bessemer screw stock. The work hardening characteristics of the austenitic alloys require that slow feeds, deep cuts and powerful rigid machines be employed for best results. Straight-chromium grades have a lower rate of work hardening than the austenitic types but comparable machining techniques are recommended. The work should be firmly supported, and tool mountings should provide maximum stiffness. It is especially impor-

Table X. Recommended Heat Treatments and Electrodes for Welding Corrosion-Resistant Castings

ACI Type	Recommended Heat Treatment		Recommended Electrode
	Pre-Weld	Post-Weld ^(a)	
CA-15	400 to 600	Cool to 300 F min, air cooled from 1125 to 1450 F	410
CA-40	400 to 600	Cool to 300 F min, air cooled from 1125 to 1450 F	420
CB-30	600 to 800	Cool to 150 F max, heat to 1450 F, air cooled ...	431
CC-50	350 to 400	Heat to 1650 F, then rapidly air cool...	446
CE-30	None	None ^(b)	309
CF-8	None	Water quenched from 1950 to 2050 F...	304
CF-20	None	Water quenched from 2000 to 2100 F...	302
CF-8C	None	None	347
CF-8M	None	Water quenched from 1950 to 2100 F...	316
CF-12M	None	Water quenched from 1950 to 2100 F...	316
CF-16F	None	Water quenched from 2000 to 2100 F...	304
CH-20	None	Water quenched from 2000 to 2100 F...	309
CK-20	None	Water quenched from 2000 to 2150 F...	310
CN-7M	400	Cool very slowly, heat to 2000 F, water quenched	(c)

(a) Time at post-weld temperature should be long enough to insure uniform heating throughout the areas and sections involved. Quenching of chromium-nickel grades should be drastic enough to insure a rapid rate of cooling from 1600 to 800 F. Air or oil quenching may be adequate with light sections and low-carbon alloys.

(b) Post-weld heat treatment usually is not necessary; however, corrosion resistance and ductility can be improved somewhat by quenching from about 2000 F.

(c) Rod of composition equivalent to cast alloy is available and should be used.

tant that the tool be kept continually entering the metal, to avoid work hardening the surface from rubbing.

Single-point high speed steel turning tools are usually ground with a 4 to 10 deg side and back rake, 4 to 7 deg side relief, 7 to 10 deg end relief, 8 to 15 deg end cutting edge angle, 10 to 15 deg side cutting edge angle, and $\frac{1}{2}$ to $\frac{1}{4}$ in. nose radius. Short stiff drills are recommended and should be kept sharp. For high-production work, the speeds given in Table XII can be increased considerably by using carbide tools.

Good lubrication and cooling are essential. The low thermal conductivities of the alloys make it most important to have the cutting fluid flood both the tool and the work. Sulfochlorinated petroleum oil containing active sulfur and about 8 to 10% fatty oil is recommended for high speed steel tools. Water-soluble cutting fluids are useful with carbide tools.

Reference to Corrosion Resistance of Stainless Steels

The 1948 ASM Metals Handbook contains two articles devoted to the important factors that influence the corrosion resistance of iron-chromium and iron-chromium-nickel alloys: "Corrosion-Resistant Castings" and "The Resistance of Wrought Stainless Steels to Corrosion".

"Corrosion-Resistant Castings", page

Table XI. Recommended Electrical Settings for Welding Corrosion-Resistant Castings

Section Thickness, in.	Electrode Diameter, in.	Current, amp	Arc Volts (max)
$\frac{1}{8}$ to $\frac{1}{4}$	$\frac{1}{8}$	45 to 70	24
$\frac{1}{8}$ to $\frac{1}{4}$	$\frac{1}{8}$	70 to 105	25
$\frac{1}{8}$ to $\frac{1}{4}$	$\frac{1}{8}$	100 to 140	25
$\frac{1}{4}$ to $\frac{1}{2}$	$\frac{1}{8}$	130 to 180	26
$\frac{1}{2}$ and over	$\frac{1}{8}$	210 to 290	27

549, outlines the considerations for their selection for service, first in general terms, and then more specifically on the basis of the particular properties of each alloy type. The latter information is divided into three groups: iron-chromium alloys, which pertains to the so-called straight-chromium alloys; iron-chromium-nickel alloys, in which the chromium exceeds the nickel content; and iron-nickel-chromium alloys, with more nickel than chromium.

"The Resistance of Wrought Stainless Steels to Corrosion", page 557, reports on factors such as: effects of composition on resistance to corrosion, effect of heat treatment on resistance to corrosion, effect of surface condition, and others. Under corrosive effects of various media, tabular data for the rate of corrosion are reported for many and varied media.

Table XII. Speeds and Feeds for Machining Corrosion-Resistant Castings

ACI Type	Rough Turning		Drilling Speed, ^(a) sfpn	Tapping Speed, sfpn
	Speed, ^(a) sfpn	Feed, ipr		
CA-15	40 to 50	0.010 to 0.030	35 to 70	10 to 25
CA-40	25 to 35	0.030 to 0.040	30 to 60	10 to 20
CB-30	40 to 50	0.020 to 0.030	30 to 60	10 to 25
CC-50	40 to 50	0.025 to 0.035	40 to 60	10 to 25
CE-30	30 to 40	0.020 to 0.025	30 to 60	10 to 25
CF-8	25 to 35	0.020 to 0.025	20 to 40	10 to 20
CF-20	25 to 35	0.020 to 0.025	20 to 40	10 to 20
CF-8C	30 to 40	0.020 to 0.025	30 to 60	10 to 25
CF-8M	25 to 35	0.020 to 0.025	20 to 50	10 to 20
CF-12M	25 to 35	0.020 to 0.025	20 to 50	10 to 20
CF-16F	45 to 55	0.020 to 0.025	30 to 80	15 to 30
CH-20	25 to 35	0.020 to 0.025	20 to 50	10 to 20
CK-20	25 to 35	0.020 to 0.025	20 to 40	10 to 20
CN-7M	45 to 55	0.020 to 0.025	30 to 60	10 to 25

(a) For high speed steel tools. About twice these speeds for carbide tools.

(b) Drilling feeds: drill diameter under $\frac{1}{8}$ in., 0.001 to 0.002 ipr; $\frac{1}{8}$ to $\frac{1}{4}$ in., 0.002 to 0.004 ipr; $\frac{1}{4}$ to $\frac{1}{2}$ in., 0.004 to 0.007 ipr; $\frac{1}{2}$ to 1 in., 0.007 to 0.015 ipr; more than 1 in., 0.015 to 0.025 ipr.

Heat-Resisting Alloys

By the ASM Committee on Heat-Resisting Alloys

THIS article supplements those on Wrought Heat-Resisting Alloys (page 562) and Heat-Resistant Castings (page 570) in the 1948 Metals Handbook. Significant changes in the data given there, as well as additional data on the same alloys and new alloys, are presented on pages 46, 47 and 48. However, the principal purpose of this article is to discuss more comprehensively the various types of elevated-temperature tests, their limitations and application to design and selection of heat-resisting alloys.

No single alloy can serve economically for a wide range of applications involving different stresses, temperatures, and expected service lives. Selection is required, and the choices are usually much more narrowly limited than for applications of constructional steels at room temperature.

The properties of heat-resisting alloys at room temperature are useful indicators of general quality and of suitability for some cold fabricating operations. For design and alloy selection, the results of tests at elevated temperature are necessary. These tests should preferably be related to the anticipated service conditions in a direct way.

Short-Time Tension Tests

Any test at elevated temperature requires greater care than at room temperature. Temperature, time, and rate of loading must be controlled. Short-time tension tests should be made in conformity with ASTM Recommended Practice E21.

Elastic properties at elevated temper-

atures are apparent, rather than real; their magnitudes depend on the increment of time between load applications; their accuracy, on the sensitivity of the extensometer. The longer the time increment and the greater the sensitivity of the extensometer system, the lower will be the observed values of all the elastic properties. Yield stress is usually taken at either 0.1 or 0.2% offset.

Although short-time tests may sometimes provide useful design data, the important effects of time at temperature are not measured. The duration of testing is usually only a few minutes, and the test measures the properties of the material only for a comparable length of time and when similarly loaded. (The short-time tensile strength is frequently used as the 0.1-hr point on a rupture curve.) The minimum temperature for plastic flow must be determined by creep and rupture tests,

Table I. Basis for Establishing Allowable Stresses
(Boiler and Pressure Vessel Codes of the ASME)

A Unfired Pressure Vessels ^(a)	
1	Elastic range: $\frac{1}{4}$ tensile strength $\frac{3}{8}$ yield strength (0.2% offset)
2	Plastic range: 100% creep strength (0.01% in 1000 hr) not to exceed 100,000-hr rupture strength
3	Intermediate range: curve connecting the two preceding ranges
B Power Boilers	
1	Elastic range: same as A above
2	Plastic range: same as A above except stress not to exceed: (a) 60% avg 100,000-hr rupture strength ^(b) (b) 80% min 100,000-hr rupture strength ^(b)
3	Intermediate range: same as A
C Bolting Steels ^(a)	
1	Elastic range: 20% tensile strength 25% yield strength (0.2% offset)
2	Plastic range: same as A above
3	Intermediate range: same as A
(a) See VIII, Appendix P. See UA-500	
(b) See I, Appendix, See A-150	

as illustrated in Fig. 1, which shows typical short-time tensile, rupture and creep data for a highly alloyed wrought heat-resisting alloy and the relations among them over a range of temperatures. Where satisfactory performance depends on the long-time strength or ductility above the elastic range, a short-time tension test is of little value.

Table I shows the basis for establishing allowable stresses according to the ASME Boiler and Pressure Vessel Code. Short-time tensile properties are usable in the so-called "elastic temperature range", where time effects and plastic flow are insignificant. It is dangerous to use such data for design unless the service temperature falls below the range where creep and other time-dependent properties begin to control the behavior. The controlling factor is indicated by comparison of data obtained by short-time and long-time tests at the temperature of interest.

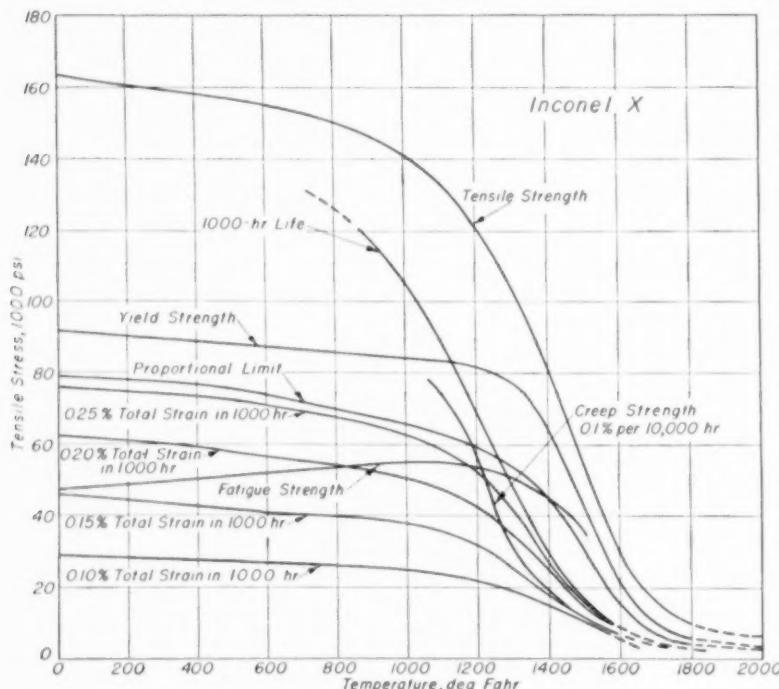
The change from low-temperature to high-temperature behavior covers a range of temperature. Ferritic alloys are usually in the high-temperature range above 700 F, and austenitic materials above 900 F.

Allowable stresses have been chosen and published for the straight chromium (ferritic) and chromium-nickel (austenitic) stainless steels over their respective temperature ranges of usefulness by the ASME Boiler Code Committee.

Stress-Rupture Tests

The most important tests used in securing data for high-temperature design are creep and rupture tests. They are closely related; both involve testing at a constant temperature under a constant load. In creep tests, deformation rates are slow. In rupture tests, the loads are high enough to cause comparatively rapid rupture.

Fig. 1. Typical Tensile Properties of Inconel X at Elevated Temperatures.
Short-time tests except as noted. Heat treatment: 4 hr at 2100 F, 24 hr at 1550 F, 20 hr at 1300 F



Supplements the articles on Cast and Wrought Heat-Resisting Alloys in the 1948 ASM Metals Handbook, pages 562 to 581

In stress-rupture tests, a series of specimens are broken at each temperature of interest, under constant load, the stresses being selected so fractures will occur in times varying from a few minutes to several hundred or thousand hours. Standard methods are published in ASTM Tentative Recommended Practice E85. Such tests can be used for determining not only the load-carrying ability, but also the high-temperature ductility up to fracture, and thus for indicating the susceptibility of the alloy to fracture with low ductility (Table II). Such behavior makes

Table II. Examples of Alloys Having Low Rupture Ductility at Elevated Temperatures

Alloy	% Elongation—		
	At Room Temp.	At 1000-hr Rupture, Temp.	Elevated Temp.
1 $\frac{1}{2}$ Mo steel	37	5 at 1000 F	
1 $\frac{1}{2}$ Si - 1 $\frac{1}{2}$ Mo steel	35	5 at 1000 F	
25 Cr - 12 Ni stainless	50	7 at 1200 F	
35 Ni - 15 Cr stainless	46	4 at 1200 F	
A-286 alloy	25	2 to 6 at 1000 F	
Inconel W	25	1 to 4 at 1200 F	

These are typical values which could be affected by heat treatment and other processing variables.

it necessary to consider the "rupture strength" of the material—the stress that causes failure at a specified time and temperature.

When the stresses and corresponding rupture times for a series of tests at one temperature are plotted on logarithmic coordinates, the relationship is nearly linear if the alloy has sufficient stability of both surface and microstructure. Figure 2 shows stress-rupture data plotted on log-log coordinates for S-590 alloy heat treated by water quenching from 2250 F and aging 16 hr at 1400 F.

The slope of the stress-rupture line varies, depending on the test temperature and the alloy under test. Usually the slope becomes greater as the test temperature is increased. If the surface or microstructure of an alloy is unstable, one or more changes in the direction of a steeper slope of the lines may occur, as shown in Fig. 3. From this plot, the rupture strengths for specified times such as 10, 100 and 1000 hr can be determined.

Rupture strengths indicate whether failure may be expected within the service life. Guided missiles are designed for a life as short as one hour or less; turbo-jet engines for military use are frequently designed for 1000-hr use.

Fig. 2. Typical Stress-Rupture and Creep Rate Data for S-590 Alloy. Heat treatment: 2250 F, water quench, 16 hr at 1400 F

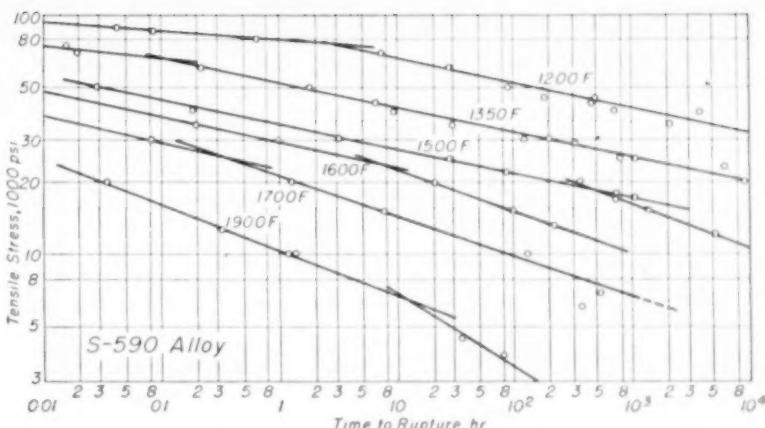
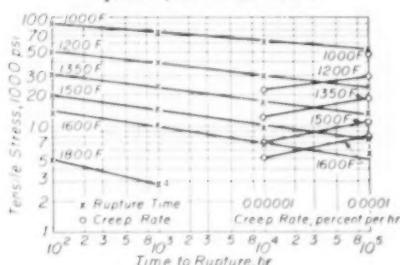


Fig. 3. Typical Stress-Rupture Data for S-590 Alloy. Heat treatment: 1 hr at 2275 F, water quench, 16 to 24 hr at 1400 F for specimens tested at 1400 F and below, 16 to 24 hr at 1500 F for tests at 1500 F, 16 to 24 hr at 1350 F for specimens tested at 1600 through 1900 F

life. Stress-rupture data can sometimes be used directly in such designs where the test period can be as long as the life of the part. For commercial steam or gas turbines, lives of 10 yr or more are guaranteed, with the design based on 100,000 hr (13 yr). Since tests of such long duration are prohibitively expensive, extrapolation of data obtained during shorter time periods is necessary.

Some stress-rupture lines are not quite straight and their slopes may increase as the testing periods become longer. This makes extrapolation of more than one log cycle (a factor of 10) open to considerable question. F. R. Larson and J. Miller have described (Trans ASME, July 1952) a method for combining the effects of time and temperature which permits the use of higher-temperature tests of reasonable duration as a guide to the extrapolation of the service temperature data. Using the Larson-Miller method, for example, the stress that will cause failure in 13 yr at 1200 F can be predicted with reasonable accuracy by a test of only 1000-hr duration at 1350 F.

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Even with good quality metal, the accuracy of rupture tests is such that the rupture life of a given specimen may be anywhere from one-half to twice the mean value. The probability that specimens from any single bar will be in error by a significant amount is great enough so that single-bar results cannot be relied on. When four or five bars are tested, whose results when plotted permit good location of a line, the stress for a given life can be determined to within $\pm 5\%$.

In the early history of the stress-rupture test, deformation and the rate of deformation were not measured, and this simplification was considered to be a great advantage over the creep test. Deformation data are still often considered unnecessary. However, in some applications, such data are important. The following lists show applications requiring deformation data and those requiring only rupture data:

Deformation Data Necessary

- Boots
- Steam valves
- Steam turbine blading
- Turbine rotors
- Turbine wheels
- Turbine casings
- Valve stems

Only Rupture Data Necessary

- Superheater tubes
- Still tubes
- Piping
- Pipe fittings
- Sheet metal parts
- Nozzle guide vanes
- Boilers

In rupture tests that evaluate alloys for applications requiring deformation data, deformations are obtained throughout the test, as in creep tests, and they are called creep-rupture tests.

Rupture strength under conditions more complex than simple tension have not been thoroughly investigated; the engineer should proceed with great caution when applying conventional stress-rupture data to more complex stress conditions.

In any application where there can be notches in a stressed part, the behavior of specimens with the same type and size of notches should be investigated. A notch as such causes a definite increase in stress (stress concentration) which is relieved by plastic flow to an extent that varies with the alloy. If the relief is great

enough, then the presence of tri-axial stress inhibits further plastic flow and strength is increased.

In the stress-rupture test of a notched specimen, the loading is in simple tension but the stresses produced by the circumferential notch are tri-axial. It is impossible to predict from results on circumferentially notched bars whether an alloy will be notch sensitive in the form of a flat bar with a groove or as a round bar with a hole.

Frequently an alloy that is not notch sensitive at short rupture times, will become notch sensitive at somewhat longer rupture times, while at still longer times it may again become insensitive to notches. This type of behavior is illustrated by Fig. 4 from W. F. Brown, Jr., M. H. Jones and D. D. Newman (Proc ASTM, 1953).

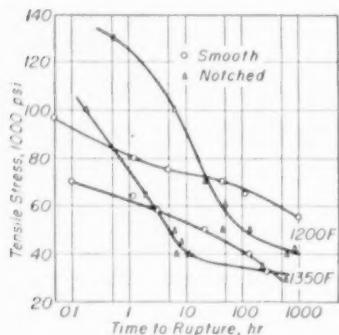


Fig. 4. Typical Rupture Data for Smooth and Notched Specimens of Haynes Alloy 88 at 1200 and 1350 F

Some of these changes are probably caused by aging or precipitation.

For elevated-temperature applications where operation under varying conditions is anticipated, design becomes more difficult. The effect of cycling load or temperature, or both, on the life of a part can only be estimated for most applications.

Slow temperature cycling above and below the mean temperature results in shorter rupture life than for steady exposure at the mean temperature. Wide temperature cycles at a rapid rate can produce thermal shock. Some jet engine manufacturers evaluate potential blade alloys by alternate rapid heating and cooling of actual blade airfoil sections, using a high-intensity flame and air-blast cooling. The use of strength characteristics alone by a designer, without consideration of the sensitivity

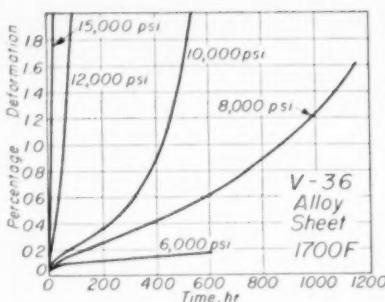


Fig. 6. Typical Curves of Time Versus Creep Deformation for V-36 Alloy Sheet Tested at 1700 F

time-deformation curve is ordinarily determined, and from this curve are obtained both the times for specified amounts of total deformation and also the creep rates for specified times.

Slow deformation at constant load and temperature is difficult to measure and is affected by slight changes in the metal or the testing conditions. Accurate and dependable long-time creep data can be obtained only by careful attention to testing technique, particularly temperature control and uniformity, and the measurement of the deformation. The necessary precautions to achieve accurate and reproducible creep test results are given in ASTM Recommended Practice E22.

Figure 6 shows time-deformation curves obtained during creep tests of V-36 alloy sheet at 1700 F. The first stage is one of decreasing creep rate immediately after loading, the second stage is characterized by approximately constant creep rate, the transition point denotes the time at which the creep rate begins to increase significantly, and the final stage is one of rapidly increasing rate of creep immediately preceding rupture. These stages are sometimes difficult to distinguish and

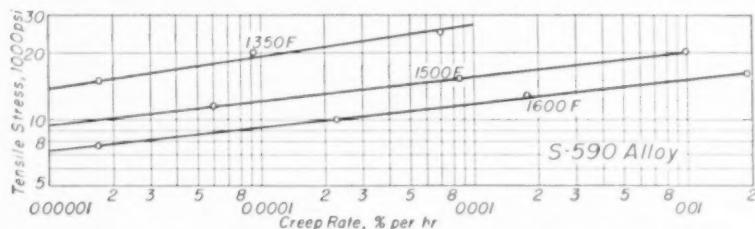


Fig. 7. Curves of Stress Versus Second-Stage Creep Rate for S-590 Alloy at High Temperature. Heat treatment: 1 hr 2300 F, water quench, 16 hr 1400 F

resulting from the change in modulus of elasticity, and the stretch from the load both during heating and at maximum temperature. Figure 5 shows data for 1-min and 10-min test periods for several sheet alloys tested at 1800 F.

Creep Tests

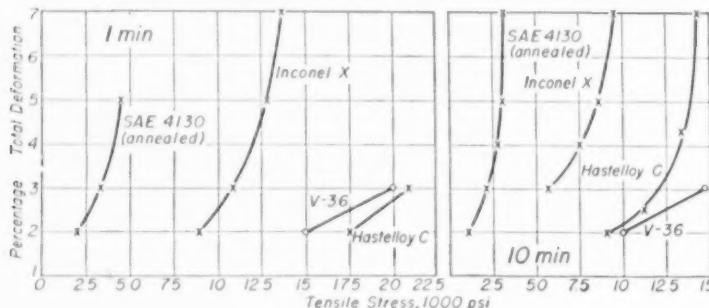
A metal capable of large deformations may creep and become useless because of loss of operating clearances or change in shape long before rupture. In a creep test, the applied stresses are lower than in a rupture test, and failure usually does not occur. A complete

may cover extended periods, depending on the alloy and temperature.

A logarithmic plot of stress versus creep rate in the second stage usually gives a straight line as indicated in Fig. 7 for S-590 alloy. These data are suitable for interpolation and some extrapolation for determining stresses for specified creep rates, such as 0.00001% per hr. One cannot assume that a rate of 0.00001% per hr is equivalent to 0.01% in 1000 hr or 1% in 100,000 hr. A straight-line relationship between stress and creep rate in the second stage is usually obtained if the alloy has enough stability of both surface and microstructure under the given test conditions; otherwise a break will occur in the straight-line relationship, in the direction of a steeper slope. Thus, extended extrapolations can be dangerous.

Relaxation Tests are a specialized type of creep test, used primarily to estimate how long a bolt or a shrink fit will remain tight. The total strain in the tests should correspond with the design stress in the parts. Stress is then continually lowered so that the total strain, elastic plus plastic, remains constant. In effect, this is a gradual substitution of plastic strain for elastic strain. Data are usually plotted as the logarithm of residual stress versus the logarithm of time, so that the stress at any desired time can

Fig. 5. Curves of Stress Versus Total Deformation for Several Heat-Resisting Sheet Alloys Tested for Very Short Times at 1800 F



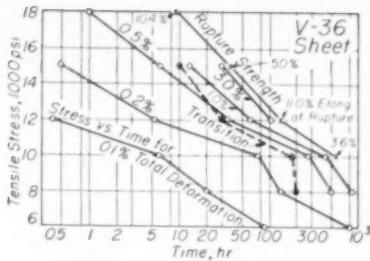


Fig. 8. Design Curves for V-36 Alloy Sheet at 1700 F. Based on Fig. 6 and rupture data. Transition line indicates where final stage of creep begins; numbers adjacent to points indicate elongation at rupture.

be determined and it can be decided whether a bolt or joint will stay tight.

Alloys such as Inconel X, type 550, A-286, Discaloy 24, K-42-B, and Refractaloy 26, which can be heat treated to high tensile, yield, and creep strengths above 1050 F, give the best service as bolting in these temperature ranges. Modified 12% Cr alloys are used up to about 1050 F. The more common ferritic bolting steels of the Cr-Mo and Cr-Mo-V types are outstanding for service applications up to and including 1000 F, and in this temperature range are used in much greater tonnages than the more highly alloyed materials.

Design Curves

In general, the plot of stress versus creep rate in the second stage is not entirely satisfactory for design, because all of the deformation occurring in the first stage is neglected, as well as the elastic strain. Therefore, many designers prefer to combine rupture and creep data in so-called design curves.

Design curves prepared from rupture-

time data and from the creep data shown in Fig. 6 for V-36 alloy tested at 1700 F are included in Fig. 8. Such a plot shows the relation between stress and time for rupture, transition point, and stress for various amounts of total deformation at a single temperature. The top curve in Fig. 8 is the usual stress-rupture time curve. Below it is sometimes shown a broken line which indicates the transition point in a creep test—the time at which the third or final stage of creep begins—which serves as a warning that any higher stress will have a rapidly increasing deformation rate leading to early failure.

The lower lines in Fig. 8 are for amounts of total deformation ranging from 0.1 to 3%, including the elastic deformation resulting from application of the load, as well as the subsequent plastic deformation in both the first and second stages of creep. These deformation data are scaled from the time-deformation curves of both creep-rupture and creep tests. Using such design curves (one for each temperature of interest), one can choose the stress that will produce not more than the limiting allowable deformation in the desired life of the part. If cyclic temperature conditions are involved, stress values should be lowered.

Impact Tests

Impact tests at a series of temperatures will show trends which can assist in the selection of alloys for applications where impact resistance is needed. The impact test specimen and type of test should conform as nearly as possible with the conditions of service to be met. High impact resistance is not necessarily indicative of high strength; for instance, cast cobalt-base alloys are lower in impact resistance than many of the wrought alloys at 1500 F, but are equal or superior in strength.

Fatigue Tests

Metals fail by fatigue at elevated temperatures, just as at room temperature. Tests can be made in alternating axial stress (tension-tension or tension-compression), alternating bending, or alternating shear (torsion) either alone or superimposed on a static stress. The normal test specimen is a fairly rigid bar of round cross section but rectangular sections, wire or sheet, can be used to simulate service requirements.

The main items to be considered in selecting conditions for elevated-temperature fatigue testing are frequency of the load changes, size of the specimen, stress pattern and temperature. Frequency within ordinary ranges has little effect on fatigue strength, as shown by tests up to about 10,000 cycles per min. This is far short of the frequencies of vibration of some high-temperature parts—for example, 5,000 to 10,000 cycles per sec for some turbine buckets. As no testing equipment is available for such high frequencies, comparisons at service frequencies are impossible. Since fatigue data for high temperatures are usually "cycles to failure", frequency merely affects the length of the test in hours. Time required for a given number of cycles can indirectly affect the results because of aging of the alloy—or, if static and fatigue stresses are combined, creep can become a factor. There is also sometimes a size effect; smaller bars have a somewhat higher fatigue strength. Thus, a test on a 2-in. diam bar at 20 cycles per sec could be misleading if applied to design of a part of $\frac{1}{2}$ -in. diam stressed at 10,000 cycles per sec.

The effect of rapid fluctuations in loading on rupture life of N-155 alloy is shown in Fig. 9. At 1350 and 1500 F dynamic superimposed loads of $\pm 25\%$ do not affect the rupture life. At higher levels of dynamic stressing, the mean stress for constant life decreases until finally, for zero mean stress, the fatigue stress for completely reversed loading is reached on the vertical axis. For this N-155 alloy, the effect of superimposed dynamic loading is more marked at the lower test temperature of 1200 F than at 1350 and 1500 F.

Figure 10 shows a marked effect of dynamic load on Nimonic 80 at 1290 F. Figure 11 is for G18B alloy, which improves with the indicated increments of superimposed dynamic load. (For data on high-temperature fatigue un-

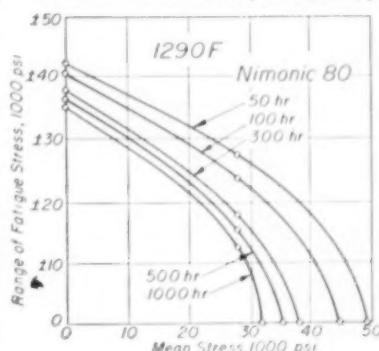
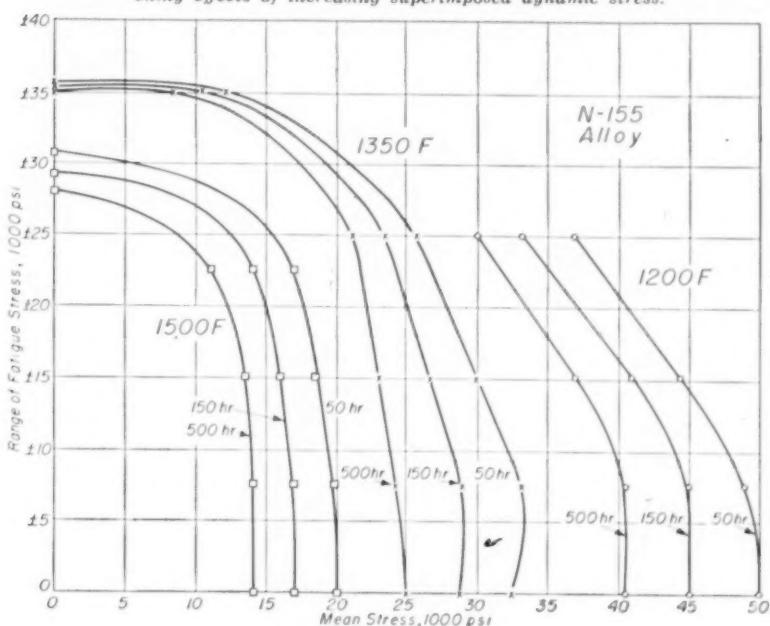


Fig. 10. Effect of Superimposed Dynamic Loading on Fatigue-Rupture Stress of Nimonic 80 (Composition Same as Nimonic 80A, in Table V)

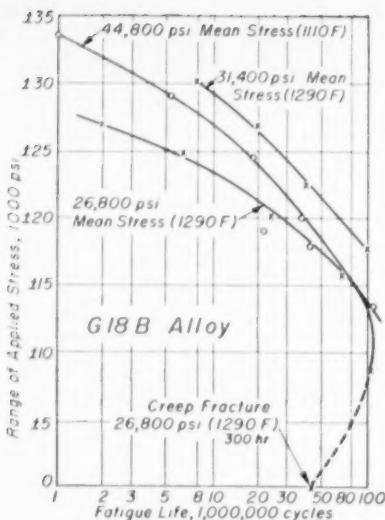


Fig. 11. Effect of Superimposed Dynamic Loading on Fatigue-Rupture Strength of G18B Alloy (13% Cr, 13% Ni, 10% Co, 2% Mo, 3% Cb, 2.5% W, 1% Si, 0.8% Mn, 0.4% C, rem Fe). Curves show strengthening effects of initial increasing superimposed dynamic stress.

der combined stresses, the reader may refer to a paper by B. J. Lazan [Proc ASTM, 1952] and references cited therein.)

Notch Sensitivity in fatigue is pronounced and depends on the geometry of the notch, the alloy in question and the temperature.

Vibration. Fatigue data can seldom be used directly in design. Most rotating machinery is designed to be in balance; resonant vibration is avoided or reduced as much as possible. Many fatigue problems arise from the fact that vibration cannot be eliminated, so that some indeterminate amount of alternating stress is unavoidable. For example, in an aircraft gas turbine, buckets are subjected to alternating bending stresses which may cause vibration, as a result of the buckets rotating past the nozzle guide vanes which direct the stream of hot gas onto the buckets. When alternating stresses may become large, the alloy should have the best combination of static and fatigue strengths. Table XIII, page 569, in the 1948 Metals Handbook shows fatigue data for some high-temperature alloys.

Table III. Creep Data for Cast Heat-Resistant Iron-Chromium-Nickel Alloys^(a)

ACI Type	% Cr	% Ni	Stress (psi) for Creep Rate of 0.0001% per Hr ^(a)			
			1400 F	1600 F	1800 F	2000 F
HC ^(b)	28	(4)	1300	750	360	...
HD	28	5	3500	1900	900	...
HE	28	10	3500	2000	1000	...
HF	20	10	6000	3200	...	...
HH ^(c)	26	12	3000	1700	1100	300
HH ^(d)	26	12	7000	4000	2100	300
HI	26	15	6600	3600	1900	800
HK	26	20	6800	4200	2700	1000
HL	30	20	7000	4300	...	...
HT	15	36	8000	4500	2000	500
HU	19	39	8500	5000	2200	600
HW	12	61	6000	3000	1400	...
HX	17	67	6400	3200	1600	600

(a) Values represent constant-temperature operation. If alloys are exposed to cyclic temperatures, lower values would apply. (b) Alloy with more than 2.5% Ni and 0.15% N. (c) Partially ferritic (ASTM B190, type I). (d) Wholly austenitic (ASTM B190, type II).

Table IV. Rupture Strength of Cast Heat-Resistant Iron-Chromium-Nickel Alloys^(a)

ACI Type	Temp → Hours	Stress (psi) for Rupture			
		1400 F 100 hr	1400 F 1000 hr	1600 F 100 hr	1600 F 1000 hr
HC ^(b)	3,300	2,300	1,700	1,300	1,000
HD	10,000	...	5,000	...	2,500
HE	11,000	...	5,300	...	2,500
HF	14,000	8,000	6,000	3,800	...
HH ^(c)	14,000	6,500	4,800	3,100	2,100
HH ^(d)	14,000	10,000	7,500	4,700	4,000
HI	13,000	8,500	7,500	4,800	4,100
HK	14,500	9,000	7,800	5,000	4,500
HL	15,000	...	9,200	...	5,200
HT	18,000	12,500	8,500	7,000	4,500
HU	15,000	...	8,000	6,000	4,500
HW	10,000	7,800	6,000	4,500	3,600
HX	13,000	...	6,700	4,000	3,500
			2,200	1,700	900

(a) Values represent constant-temperature operation. If alloys are exposed to cyclic temperatures, lower values would apply. (b) Alloy with more than 2.5% Ni and 0.15% N.

(c) Partially ferritic (ASTM B190, type I). (d) Wholly austenitic (ASTM B190, type II).

Damping Capacity. Particularly with resonant vibration, damping capacity can play a more important part than fatigue strength in avoiding fatigue failures. If no energy were required to maintain a part in vibration (that is, if it had zero damping capacity) even the smallest force would develop destructive stresses rapidly; only the dissipation of energy limits vibrational stresses, especially the total damping of the assembly—that is, the material damping, mechanical damping by the means of attachment, and aerodynamic damping. As in designing for fatigue, it is best to make the total damping as high as possible whenever possibilities of resonant vibration exist.

Stability

Stability of surface and microstructure are both important. The alloy composition for optimum strength is not always the best for stability; chromium, nickel and cobalt contents are adjusted to provide satisfactory resistance to oxidation and corrosion, along with acceptable high-temperature strength. Oxidation resistance is obtained by chromium contents of 12% or more in the ferritic stainless steels; the stronger austenitic chromium-nickel steels, and the chromium-cobalt and chromium-nickel-cobalt alloys contain 14 to 25% Cr.

Resistance to local or grain boundary attack and penetration may differ among alloys having otherwise satisfactory resistance to oxidation. When this occurs, strength and ductility may be significantly impaired, and the lo-

calized areas of attack are focal points for starting of fatigue failure.

High-temperature alloys differ widely in resistance to oxidation and corrosion. For example, page 571 of the 1948 Handbook shows oxidation and sulfur-corrosion data for commercial heat-resistant iron-chromium-nickel cast alloys. Considerable differences were observed among the various alloys. Also, the rates of oxidation and corrosion that would be permissible in some applications—such as cast furnace parts or still-tube supports—might be wholly unacceptable in gas-turbine blading.

Even though heat treatments are carefully chosen to stabilize high-temperature alloys as much as possible before use, microstructural changes do take place during service, and can result in lower static, impact and fatigue strengths at high temperature, increased notch sensitivity, and harmful reductions in ductility. The most commonly encountered form of instability results from aging or precipitation. The complete processing history of an alloy—melting practice, casting and forging practice, and heat treatment prior to high-temperature service—can greatly influence subsequent structural changes.

Structural instability can be determined by changes in hardness, microstructure, impact properties, fracture ductility, magnetic permeability, rupture, and creep strength. Changes in the slopes of curves of stress versus rupture time and stress versus creep rate are usually the result of changes in the stability of the surface or the microstructure, or both.

Figure 3, rupture data for S-590 alloy reported by N. J. Grant and A. G. Bucklin (Trans ASM, 1950), illustrates slope changes which may occur during extended high-temperature testing, partly as a result of instability.

Design Considerations

The following discussion of design is especially pertinent to sand and permanent-mold castings of the iron-chromium-nickel alloys. The design stress is usually taken as some percentage of the stress that will produce a creep rate of 0.0001% per hr. Values of 25 to 50% of this "limiting" creep stress are frequently chosen for parts to be used at a constant temperature. If the casting is repeatedly heated and cooled, the allowable stress is reduced to a smaller percentage of the creep

strength at the maximum operating temperature.

Loss of metal from corrosion is usually neglected in design, except in alloy selection. Maximum penetration rates of 0.05 in. per yr or less in the working atmosphere and temperature are considered low enough. Obviously, corrosion losses are of more concern in thin than in thick sections.

Conditions of temperature, support and structural complexity all enter into the choice of design stress. Stationary parts subject to static loading may be stressed more highly than moving parts carrying impact loads under otherwise similar conditions of temperature and atmosphere; parts that are continually rotating, such as shafts, can be designed at even higher percentages of the limiting creep stress. Consideration must also be given to thermal gradients caused by uneven heating and cooling, as in furnace hearths or trays carrying cold loads, or beams extending into or through furnace walls.

Simple wedge-shaped pieces, completely supported and uniformly heated, represent the simplest type of structure. From this ultimate in simplicity, casting designs may vary to uniform-section parts, uniform sections with multiple intersections, nonuniform sections, and nonuniform sections with multiple intersections. For the more complex designs, the effects of thermal

gradients and conditions of support are more difficult to analyze, and the selection of conservative design stresses is recommended.

Alloy Data

Since publication of the 1948 Metals Handbook, additional data on iron-chromium-nickel cast alloys have become available, and many new heat-resistant alloys have been developed. Also, several alloys in the 1948 edition are no longer made commercially.

Cast alloys of the iron-chromium and iron-chromium-nickel types are available in grades corresponding to the standard wrought stainless steels, as well as in a number of compositions not usually obtainable in wrought form. Heat-resistant castings usually contain considerably more carbon than the wrought alloys. The strengthening influence of carbon contributes to the generally superior creep and rupture properties of cast alloys, compared with wrought compositions of similar chromium and nickel contents. Also, the coarser grain structure in castings doubtless contributes to their higher creep resistance.

Representative creep and rupture data for the standard cast heat-resistant alloys are given in Tables III and IV, respectively.

Table V lists the chemical composi-

tions of selected wrought and cast heat-resistant alloys and Table VI shows the stresses to produce rupture in 100 and 1000 hr at temperatures between 1200 and 1800 F, after conventional processing and heat treatment. The rupture strengths are intended only as a guide to the relative strengths of the various alloys. Since most of the alloys are sensitive to variations in processing and heat treatment, these data should not be used for design purposes.

The first group in Table V lists the iron-chromium-nickel alloys. Included in this group are alloys such as Timken 16-25-6 and 19-9DL, which have often been used in the "hot-cold worked" (at 1200 to 1400 F) condition for turbo-supercharger and gas turbine rotors. This working increases the tensile and yield strengths of these alloys. They are not substantially hardened or strengthened by heat treatments.

Other alloys in this group, such as A-286 and Discaloy 24, contain additions of titanium and aluminum and are heat treatable. These alloys are never used in the hot-cold worked condition.

The cobalt-containing alloys in the second group are intended for higher-temperature service than the iron-chromium-nickel alloys, and are normally used in the solution treated or solution treated and aged condition. One type is strengthened by additions

Table V. Nominal Compositions of Heat-Resisting Alloys

Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Ti	Al	Fe	Other
Iron-Chromium-Nickel Alloys													
Wrought Alloys													
A-286	0.08 ^(a)	1.25	1.0 ^(a)	14.75	25.5	....	1.25	....	....	2.10	0.35 ^(a)	Rem	V 0.25
Croloy 15-15N	0.15 ^(a)	2.0 ^(a)	0.75 ^(a)	16.0	15.0	....	1.55	1.40	1.05	....	....	Rem	N 0.15 ^(a)
Discaloy 24	0.04	1.38	1.00	13.5	26.2	....	3.9	....	....	1.61	0.11	Rem	....
H R. Crown Max	0.23	0.65	1.16	23.2	12.3	....	....	3.0	....	....	....	Rem	....
Haynes Alloy 88	0.07	1.50	0.50	12.5	15.0	....	2.0	0.6	....	....	0.6	....	B 0.15
Incoloy T	0.10	1.0	0.4	20.5	32.0	....	....	....	....	1.0	....	Rem	....
S-598	0.42	1.5	0.8	18.4	20.0	....	4.0	4.0	4.0	....	....	Rem	....
Timken 16-25-6	0.10	1.35	0.70	16.0	25.0	....	6.0	....	....	....	....	Rem	N 0.15
19-9 DL	0.30	1.10	0.60	19.0	9.0	....	1.25	1.2	0.40	0.30	....	Rem	....
19-9 DX	0.30	1.00	0.55	19.2	9.0	....	1.50	1.2	....	0.55	....	Rem	....
Cobalt-Nickel-Chromium-Iron Alloys													
Wrought Alloys													
K-42-B	0.05	0.7	0.7	18.0	43.0	22.0	....	....	....	2.5	0.2	13.0	....
N-155	0.15	1.5	0.5	21.0	20.0	20.0	3.0	2.5	1.0	....	....	Rem	N 0.15
Refractaloy 26	0.05	0.7	0.7	18.0	37.0	20.0	3.0	....	....	2.8	0.2	18.0	....
Refractaloy 80	0.10	0.6	0.7	20.0	20.0	30.0	10.0	5.0	....	....	....	14.0	....
S-590	0.42	1.25	0.4	20.5	20.0	20.0	4.0	4.0	4.0	....	....	24.0	....
S-816	0.38	1.20	0.4	20.0	20.0	43.0	4.0	4.0	4.0	....	....	4.0 ^(a)	....
V-36	0.31	0.9	0.5	25.0	20.0	42.0	4.0	2.6	2.2	....	....	3.0	....
Nickel-Base Alloys													
Wrought Alloys													
Hastelloy Alloy X	0.15	....	....	22.0	45.0	....	9.0	....	....	....	....	Rem	....
Inco 700	0.10	0.05	0.2	15.0	49.0	28.0	3.0	....	....	2.0	3.0	0.5	....
Inco 739	0.07	0.05	0.2	15.0	77.0	....	....	....	....	1.7	2.7	1.0	....
Inconel	0.04	0.35	0.20	15.5	76.0	....	....	....	....	....	....	1.0	....
Inconel W	0.04	0.60	0.25	15.0	75.0	....	....	....	....	2.5	0.6	7.0	....
Inconel X	0.03	0.5	0.3	15.0	73.0	....	....	....	....	0.6	2.3	0.9	6.5
Inconel X, 550	0.03	0.5	0.3	15.0	73.0	....	....	....	....	0.6	2.5	1.1	6.5
M-252	0.15	1.0	0.65	19.0	Rem	10.0	10.0	....	....	2.5	0.87	5.0 ^(a)	....
Nimonic 75	0.12	0.4	0.6	20.0	76.0	....	....	....	....	0.4	0.06	2.4	....
Nimonic 80A	0.05	0.70	0.50	20.0	76.0	....	....	....	....	2.3	1.0	0.5	....
Nimonic 90	0.08	0.50	0.40	20.0	58.0	16.0	....	....	....	2.3	1.4	0.5	....
Waspaloy	0.10 ^(a)	1.0 ^(a)	0.75 ^(a)	19.5	Rem	13.5	4.25	....	....	2.50	1.25	2.0 ^(a)	....
Cast Alloys													
Hastelloy Alloy B	0.10	0.8	0.7	1.0	65.0	....	28.0	....	....	....	....	5.0	....
Hastelloy Alloy C	0.10	0.8	0.7	16.0	57.0	....	17.0	4.0	....	....	....	5.0	....
Cobalt-Based Alloys													
Wrought Alloy													
Haynes Alloy 25 (L605)	0.12	1.50	1.0	20.0	10.0	51.0	....	15.0	....	....	....	1.0	....
Cast Alloys													
Haynes Alloy 21	0.25	0.60	0.60	27.0	3.0	62.0	5.0	....	....	....	....	1.0	....
" " 30 (422-15)	0.40	0.60	0.60	24.0	17.0	51.0	6.0	....	....	....	....	1.0	....
" " 31 (X-40)	0.40	0.60	0.60	25.0	10.0	55.0	....	8.0	....	....	....	1.0	....
" " 36	0.40	1.2	0.50	19.0	10.0	54.0	....	14.5	....	....	....	1.0	B 0.03

(a) Maximum

of molybdenum, tungsten and columbium; the other, which may also contain some molybdenum, tungsten and columbium, has additions of titanium and aluminum for greater response to heat treatment.

Development of the high-strength heat treatable nickel-base alloys such as Inconel X, 550; Inco 700; M-252; and Waspaloy was accelerated by the necessity for new alloys to replace, in part, the cobalt-base compositions such as S-816, since the cobalt supply was insufficient for the entire U. S. production of jet engines.

The fourth group lists the cobalt-base alloys, cast and wrought. Many of the cast alloys have been used for turbosupercharger buckets and aircraft gas turbine guide vanes and buckets.

The summary presented as Fig. 12 shows the curves of stress for rupture in 1000 hr versus temperature for many of the alloys discussed and their positions relative to other commercial and experimental alloys. Among the experimental materials shown are molybdenum alloys, although no adequate method has been found for protecting them from oxidation at the elevated temperatures where they would be most usefully applied for their strength.

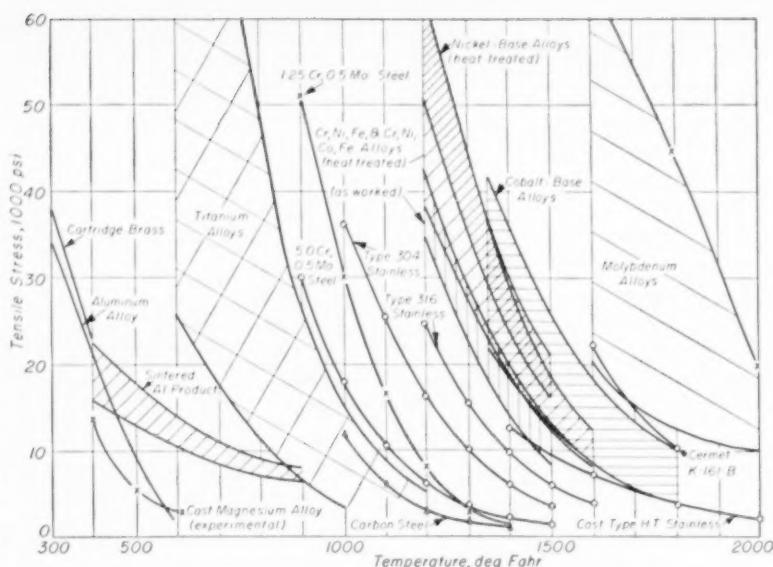


Fig. 12. Stress-Temperature Curves for Rupture in 1000 Hours for Various Commercial and Experimental Alloys

Table VI. Typical Stress-Rupture Properties of Heat-Resisting Alloys

Alloy	Stress (1000 psi) to Rupture in 100 and 1000 Hours									
	1200 F		1350 F		1500 F		1600 F		1800 F	
	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr
Wrought Alloys										
A-296	61.0	48.0	35.0	21.5	13.8	7.7	....	....	....	....
Croloy 15-15N	....	....	....	18.0	....	10.0	....	....	....	....
Discaloy 24	55.0	41.0	32.0	20.0	15.0	....	....	....	....	....
H.R. Crown Max	29.5	24.5	18.5	13.5	....	....	....	....	....	....
Haynes Alloy 88	59.0	49.0	42.0	31.0	25.5	16.0	13.5	....	....	....
Incoloy T	33.0	26.1	20.1	14.7	10.8	7.0	....	....	....	....
S-568	41.0	30.0	25.0	18.0	15.0	10.0	....	....	....	....
Timken 16-25-6	45.0	34.0	25.0	17.0	13.5	9.0	....	....	....	....
19-9 DL	52.0	38.0	28.0	19.0	17.0	10.0	....	....	....	....
19-9 DX	52.5	42.0	....	....	....	....	....	....	....	....
Iron-Chromium-Nickel Alloys										
K-42-B	66.0	40.0	37.0	27.0	17.5	11.0	....	....	....	....
N-155	50.0	40.0	31.0	24.0	18.0	13.0	12.0	8.0	5.0	2.5
Refractaloy 26	80.0	63.0	51.0	38.0	27.0	18.0	....	....	....	....
S-590	48.0	38.0	30.0	22.0	22.0	16.0	12.5	9.0	5.6	3.5
S-816	60.0	45.0	36.0	28.0	24.0	17.5	14.0	9.5	5.5	3.0
V-36	....	....	35.0	26.5	23.0	18.0	15.0	11.0	8.5	5.0
Cobalt-Nickel-Chromium-Iron Alloys										
Nickel-Base Alloys										
Hastelloy Alloy X	44.5	30.5	26.0	18.5	15.5	10.0	....	....	....	....
Inco 700	....	....	73.0	60.0	42.0	30.0	28.0	18.5	6.5	3.5
Inco 739	....	....	....	....	34.0	20.0	19.0	11.0	5.3	....
Inconel	22.0	14.5	10.5	6.8	5.7	3.7	4.2	2.7	2.5	1.6
Inconel W	74.0	54.0	45.0	30.0	19.0	11.5	7.5	4.8	3.2	....
Inconel X, 550	....	....	....	....	34.0	21.0	18.0	10.2	3.3	....
M-252	....	....	52.0	35.0	29.0	18.0	16.0	10.0	....	....
Nimonic 80A	67.3	56.0	48.0	36.0	24.0	15.5	14.0	8.5	....	....
Nimonic 90	76.1	63.0	50.6	38.0	28.0	17.9	....	....	....	....
Waspaloy	....	....	57.5	....	31.5	20.0	19.5	....	....	....
Cast Alloys										
Hastelloy Alloy B	51.0	40.5	35.0	25.5	18.5	12.7	....	....	....	....
Hastelloy Alloy C	49.5	42.5	32.0	25.0	19.0	14.5	13.2	9.2	....	....
Cobalt-Base Alloys										
Wrought Alloy										
Haynes Alloy 25 (L605)	70.0	58.0	43.0	33.0	23.0	17.0	15.5	10.5	7.0	3.8
Cast Alloys										
Wrought Alloy										
Haynes Alloy 21	51.0	44.2	32.0	22.0	22.0	14.2	16.7	13.2	9.4	7.0
" " 30 (422-19)	....	....	47.0	36.0	28.6	21.7	15.8	14.8	10.0	7.1
" " 31 (X-40)	55.0	46.0	45.0	33.0	28.4	23.4	21.0	18.0	11.3	9.8
" " 36	....	....	48.0	41.5	29.0	25.5	23.0	18.5	10.5	7.2

Nodular Cast Iron

By the ASM Committee on Nodular Iron

NODULAR cast iron, also known as nodular graphite iron, ductile iron, spherulitic iron, spheroidal graphite iron and SG iron, is cast iron in which the graphite is present as tiny balls or spherulites of characteristic structure, instead of as flakes, as in gray iron, or compacted aggregates, as in malleable iron (Fig. 1).

The total carbon content of nodular iron is the same as in gray iron. Spherulitic graphite particles form during solidification of nodular iron because of the presence of a few hundredths of 1% of magnesium, cerium or certain other elements in the molten iron just before casting. The discovery of the effectiveness of these agents was first announced in 1948, and patents have been granted in the United States, England and many other countries. With either the magnesium or cerium method, the final sulfur content of the iron must be below about 0.015% for the treatment to be effective.

A variety of matrix structures can be obtained by alloying or heat treatment. Of the many combinations of mechanical properties, ASTM specifications cover two commercial grades, designated as 60-45-10 and 80-60-03 (Table I). The three numbers in the designation refer to minimum tensile strength in 1000 psi, minimum yield strength in 1000 psi, and minimum elongation in %, respectively.

Processing

The composition and fluidity of the melt permit formation of spherulitic graphite in sections from $\frac{1}{8}$ to 40 in.; thus, castings of complex shape can be produced with desirable combinations of strength and ductility. A variety of mold materials have been used successfully—green sand, dry sand, shell molds, and permanent metal molds as used in centrifugal casting of pipe.

Stress Relieving at 1000 to 1050 F is generally applied to castings having

abrupt changes in section that cause residual stresses during cooling in the mold. The castings are sometimes cooled to below 750 F before being removed from the furnace. This heat treatment causes only slight changes in the mechanical properties of pearlitic or ferritic irons; temperatures above 1100 F will decrease hardness and strength and increase elongation.

Ferritizing Anneal. The amount of ferrite in the as-cast matrix depends on composition and rate of cooling, and may approach 100%, which gives maximum ductility, toughness and machinability. The matrix can be completely ferritized by holding at about 1300 F for 1 to 5 hr, depending on the composition, section size and amount of pearlite in the as-cast structure, followed by cooling at any convenient rate. If primary carbides are present, they are converted to spheroidal graphite by

heating at 1600 to 1700 F for 1 to 5 hr. Slow cooling (25 to 100 F per hr) to about 1275 F and holding for 3 to 5 hr, converts the matrix to ferrite. These treatments will produce iron softer than 190 Brinell, with tensile strength 60,000 to 75,000 psi, yield strength 45,000 to 55,000 psi, and elongation 10 to 25%.

Pearlitic and Martensitic Structures. If higher hardness and strength are required, nodular iron may be heat treated. Pearlitic structures are obtained by air cooling from 1600 to 1650 F. (Some ferrite may be formed if the metal is held at 1400 to 1500 F after austenitizing, and then cooled in air.) Martensite is produced by quenching in oil or water from 1600 to 1700 F. Response to tempering depends on the as-quenched structure, which is controlled by section size and hardenability, as in steel. The effect of tempering temperature on tensile and yield strengths, hardness and elongation is given in Fig. 2.

Hardenability depends on the carbon and alloy contents of the matrix; end-quench hardenability curves are similar to those for medium-carbon steels of similar alloy content. Austenitizing nodular iron at higher temperature

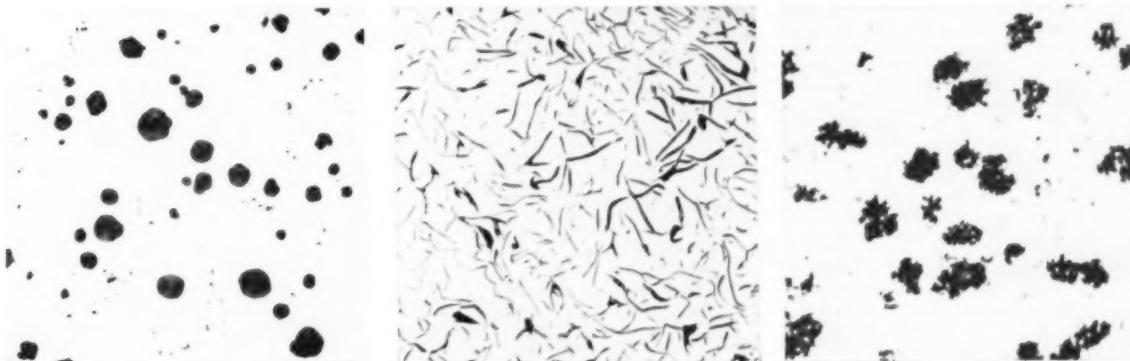
Table I. Summary of Principal Specifications for Nodular Iron

Specification	Class or Grade ^(a)	Usual Condition	Minimum Tensile Strength, psi	Minimum Yield Strength, psi	Minimum Elongation in 2 in., %
Society of Automotive Engineers					
AMS 5315 ^(b)	.....	Annealed	60,000	45,000	15 ^(c)
AMS 5316 ^(b)	.....	As cast	80,000	60,000	3 ^(d)
American Society for Testing Materials					
A339-51T	60-45-10	Annealed	60,000	45,000	10
A339-51T	80-60-03	As cast	80,000	60,000	3
Military					
MIL-I-17166A ^(e)	.....	Annealed	60,000	40,000	15
MIL-I-11466	1(120-90-02)	(f)	120,000	90,000	2
MIL-I-11466	2(100-75-04)	(g)	100,000	75,000	4
MIL-I-11466	3(85-60-06)	Heat Treated	85,000	60,000	6
MIL-I-11466	4(80-60-03)	As cast or HT	80,000	60,000	3
MIL-I-11466	5(60-45-10)	Annealed	60,000	45,000	10
MIL-I-11466	6(60-40-18)	Annealed	60,000	40,000	18

(a) The three numbers in the designation refer to minimum tensile strength in 1000 psi, minimum yield strength in 1000 psi, and minimum elongation in %, respectively.
(b) Chemical requirements are as follows: 3.2 to 4.0% total C; 0.8% max Mn; 1.7 to 2.5% Si (extended to 2.8% in castings below $\frac{1}{2}$ in. thick, provided P is held to 0.05% max); 0.08% max P. (c) When test specimens are taken directly from castings, minimum elongation is 10%. Specified hardness maximum is 190 Brinell. (d) When test specimens are taken directly from castings, minimum elongation is 2%. Specified hardness range is 202 to 269 Brinell. (e) Minimum ferrite content of 90% required in microstructure. Specified hardness maximum is 190 Brinell. Chemical requirements are as follows: 3.0% min total C; 2.5% max Si; 0.08% max P; carbon equivalent, 4.5% max. (Carbon equivalent limit is applicable only to castings having sections of 2 in. or over.) (f) Normalized or oil quenched, and tempered. (g) Normalized and tempered.

This subject is not dealt with in the 1948 ASM Metals Handbook.

Fig. 1. Nodular Iron (Left); Gray Iron (Center); Malleable Iron (Right). All $\times 66$



(for instance, 1750 instead of 1550 F) gives higher hardenability because of increased solution of carbon from the matrix. Pearlite is the most favorable matrix structure prior to heating for quench-hardening. If the prior structure is ferrite, more time is required for solution of carbon during austenitizing. The maximum hardness of as-quenched nodular iron is lower than for steels, because of the soft graphite. For service involving wear resistance, nodular iron can be flame or induction hardened to Rockwell C 53 to 58, with the microhardness of the matrix equivalent to Rockwell C 63 to 65.

Machinability of nodular iron is superior to that of gray irons of similar hardness (and lower strength). Results of comparative lathe turning tests are shown in Fig. 3. The best results were obtained with an annealed nodular iron and an annealed gray iron, which produced about the same tool life. However, the nodular iron was considerably harder and stronger than the gray iron. The cutting speeds for as-cast gray irons were about the same as for as-cast nodular iron of similar hardness but higher strength.

Engineering Properties

Engineering properties of nodular irons depend on chemical composition and heat treatment as they affect the microstructure of the matrix and, to a minor degree, on the quantity and size of graphite spherulites.

Ferritic Irons, as considered here, are those having a maximum of 10% pearlite in the microstructure and can be produced as cast or by annealing irons containing pearlite with or without massive carbide. By appropriate choice of alloy content (particularly silicon) and manufacturing variables, the mechanical properties of ferritic irons

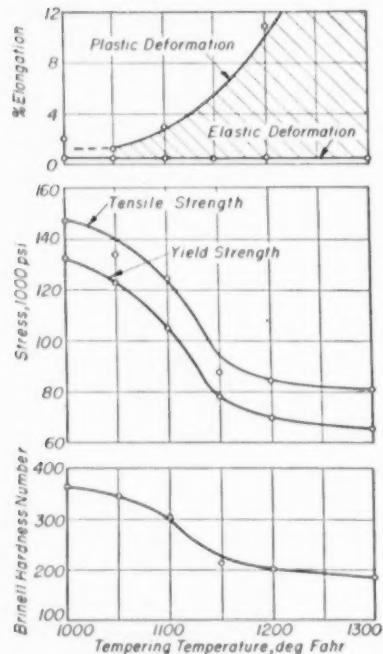


Fig. 2. Effect of Tempering Temperature on Mechanical Properties of a Single Nodular Iron

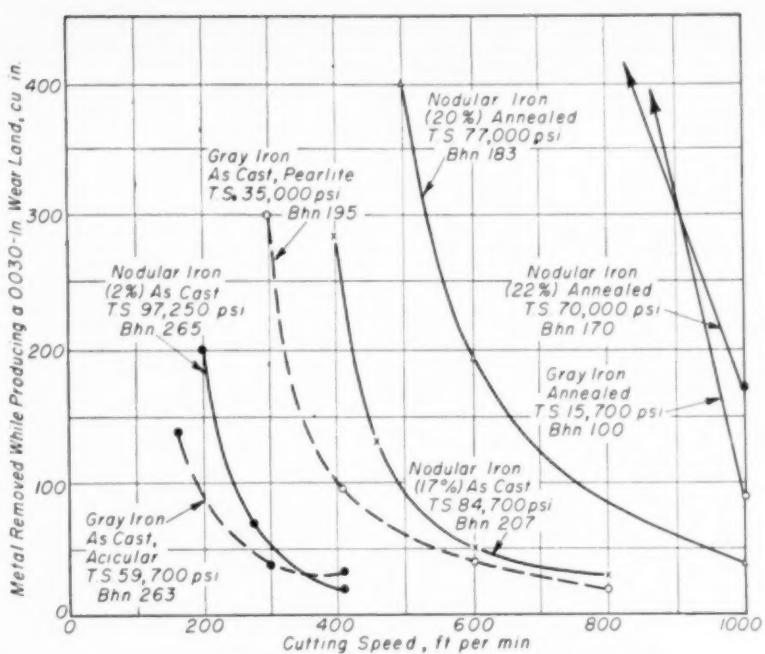


Fig. 3. Comparisons of Carbide Tool Life in Machining Three Gray Irons and Four Nodular Irons. Percentages in parentheses signify elongations of the nodular irons in standard tension tests.

can be varied within the ranges shown in Table II.

Pearlitic Irons can be produced as cast or by normalizing. The significant variables affecting the mechanical properties are: amount of pearlite, fineness of pearlite, chemical composition and tempering cycle. Because the cooling rate from 1600 F affects the first two variables, pearlitic irons are sensitive to section size; heavy sections are softer and more ductile than light sections; composition must be adjusted to the section size. The properties of pearlitic irons can be varied within the ranges shown in Table II.

Quenched Structures, whether martensitic or bainitic, are usually tempered. Irons with tensile strength of about 200,000 psi and hardness about 440 Brinell have low ductility. Ductility increases with decreasing tensile strength and hardness (Table II).

Austenitic Irons are highly alloyed types which retain their austenitic structure down to at least -75 F. Refrigeration below this temperature will partially transform these to martensite. These irons are of interest because of their corrosion resistance and creep

properties at elevated temperatures.

Tensile Strength. The relation between tensile strength and hardness is shown in Fig. 4 for the as-cast and annealed conditions over the range from 130 to 275 Brinell, and for the normalized and quenched and tempered conditions over the range from 200 to 400 Brinell. The K factor (tensile strength divided by Brinell hardness

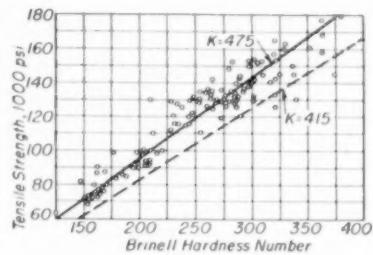


Fig. 4. Relation of Tensile Strength to Brinell Hardness of Nodular Irons. As Cast and As Annealed (Broken Line), and Normalized, and Quenched & Tempered (Solid Line)

Table II. Mechanical Properties of Basic Types of Nodular Iron

Type	Alloy Content	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., %	Brinell Hardness Number
Ferritic	Low ^(a)	55,000	35,000	25	130
Ferritic	High ^(a)	90,000	70,000	12	210
Pearlitic	Low ^(b)	80,000	60,000	10	200
Pearlitic	Low ^(b)	130,000	90,000	7	275
Pearlitic	High	130,000	110,000	2	275
Quenched		100,000	80,000	10	215
Quenched		150,000	130,000	2	320
Austenitic	(c)	60,000	30,000	40	130
Austenitic	(d)	60,000	40,000	10	160

(a) If achieved by silicon, impact will be impaired. (b) Normalized. (c) 3.00% C, 2.50% Si, 20.0% Ni, 2.0% Mn. (d) 3.00% C, 2.0% Si, 20.0% Ni, 1% Mn, 1.5% Cr.

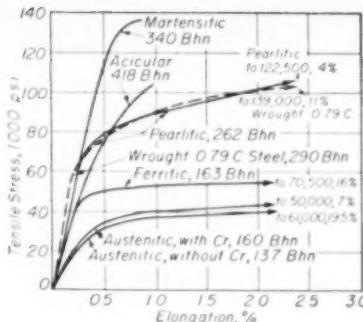


Fig. 5. Stress-Strain Curves of Nodular Irons (1-In. Y-Blocks)

number) is about 415 for the as-cast and annealed conditions and about 475 for normalized or quenched and tempered irons at hardness higher than about 300 Brinell. The approximate ratio of yield strength to tensile strength for the various conditions is:

As cast	0.75
Annealed	0.75
Normalized	0.60 to 0.75
Quenched and tempered	0.75 to 0.90

Elongation in excess of 10%, as cast, can be obtained in castings 3/16 in. thick using unalloyed nodular iron. In alloy nodular iron, ductility decreases with decreasing section size and in sections of about 1/4 in. becomes very low because of fully pearlitic structures. Sections less than about 1/4 in. thick in alloy nodular iron are likely to contain primary carbide. Castings involving sections 6 by 6 by 1/8 in. or 3 by 3 by 1/16 in. can be cast but require heat treatment for ductility and machinability. Precision castings are therefore limited, if used as cast, to sections of about 3/16 in. in unalloyed nodular iron and about 1/4 in. in alloyed iron.

Modulus of Elasticity. Typical stress-strain curves for several types of nodular iron in tension are shown in Fig. 5. The modulus of elasticity is from 21 to 25 million psi, and is not much affected by heat treatment.

Impact. Charpy notched-bar impact

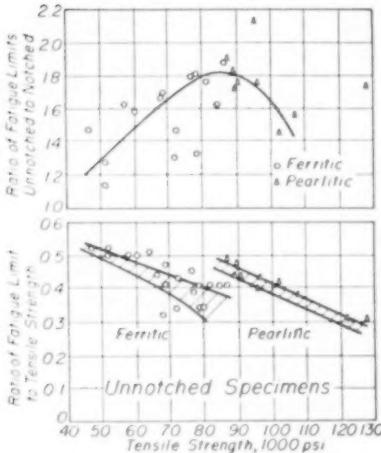


Fig. 6. Fatigue Data for Nodular Irons. Top: Relation between unnotched and notched specimens. Bottom: Ratio of fatigue limit to tensile strength for unnotched specimens

Table III. Tensile Properties of Nodular Iron at 800, 1000 and 1200 F

Property	Grade 80-60-03			Grade 60-45-10		
	800 F	1000 F	1200 F	800 F	1000 F	1200 F
Short-Time Tension Tests						
Tensile strength,						
1000 psi	55 to 85 ^(a)	33 to 50 ^(a)	15 to 25 ^(a)	40 to 45 ^(b)	23 to 27 ^(b)	10 to 12 ^(b)
Elongation in 2 in., %	1 to 3	2 to 6	8 to 16	8 to 15	4 to 10	10 to 20
Creep Tests						
Stress, 1000 psi, to produce a min creep rate of 0.0001% per hr	11 to 22	1.7 ^(c)	0.5 ^(c)	14 to 25 ^(d)	4 ^(c)	0.6 ^(c)
Stress, 1000 psi, 100 hr	40 to 54	17 ^(c)	3.8 to 4.8	30 to 35	10 ^(c)	3.3 to 3.4
Stress, 1000 psi, 1000 hr	30 to 40	9.1 ^(c)	2.4 to 2.9	25 to 27	7.5 ^(c)	2.2
(a) Range caused by variations in chemical composition and the relative amounts of pearlite and ferrite. (b) Range caused by variations in chemical composition. (c) Small amount of data available. (d) Important—These values are for nodular iron containing more than 0.5% Mn, 0.06% P and 0.5% Cu. When manganese and phosphorus are lower, this creep stress is lower; nodular iron with 0.4% Mn, 0.017% P, 0% Cu gave 8500 psi.						

values for ferritic nodular iron above the transition temperature are in the range 10 to 17 ft-lb, depending on the structure and total content of silicon,

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Canada Iron Foundries, Ltd.

phosphorus and manganese. Silicon should be kept below about 2.5%, phosphorus below about 0.08%, and manganese below about 0.50% for maximum toughness. Massive carbides and pearlite also raise transition temperature.

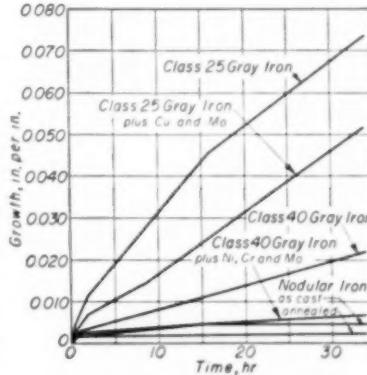


Fig. 7. Rate of Growth of Nodular and Other Irons for Short Times at 1650 F. Specimens were heated to 1650 F, held 1, 2, 4, 8 and 22 hr, furnace cooled and measured (Eagan)

Fatigue. Figure 6 shows the relation between fatigue ratio (ratio of fatigue limit for unnotched specimens to tensile strength) and the tensile strength of ferritic and pearlitic irons. The fatigue ratio decreases as tensile strength increases for both types of iron, but pearlitic iron has higher fatigue limit than highly alloyed ferritic iron of the same strength. The fatigue notch factor (the ratio of the fatigue limit for unnotched specimens to fatigue limit for notched specimens) increases with silicon content for both ferritic and pearlitic irons. However, silicon decreases the notch fatigue of pearlitic irons. In Fig. 6 the ratio is plotted against tensile strength; the curve reaches a maximum at about 85,000 psi tensile strength.

Resistance to Oxidation. In a heating test for 100 24-hr cycles (each cycle, 4 hr to heat to 1750 F, 7 hr at 1750 F, 13 hr furnace cool to between 600 and 700 F) both commercial grades of nodular iron showed oxide penetration at the rate of 0.5 in. per yr. Class 40 gray iron was completely oxidized in 45 cycles (rate, 1.5 in. per yr). Nodular iron containing 6% Si oxidized about one-tenth as rapidly as the normal grades; however, 6% Si iron is brittle at room temperature; 4% Si has been used as a compromise between oxidation resistance and ductility.

Resistance to Growth. Figure 7 shows the resistance to growth of several types of iron in a 36-hr test (T. E. Eagan, Foundry, Dec 1950). In tests of longer duration (6696 hr at 1000 F) the ferritic grade of nodular iron (60-45-10) showed only about one-tenth the growth exhibited by the pearlitic grade (80-60-03). The difference is caused by graphitization of pearlite in the 80-60-03 iron, rather than by any significant difference in oxidation resistance. Growth of flake graphite irons was 0.36 to 0.54 in., compared with 0.027 and 0.24 in., respectively, for the ferritic and pearlitic nodular irons.

Properties at Elevated Temperature. Short-time tensile strength shows a slight decrease up to about 600 F, and then falls off more rapidly with increasing temperature; at 900 F the iron retains about 50% of its room-temperature strength. Simultaneously, the ductility decreases mildly and reaches a minimum at about 900 F, after which it increases rapidly. The ranges of properties at three temperatures are given in Table III.

There is some evidence that the manganese and copper should both be above 0.5% and phosphorus above

0.06% in ferritic nodular irons to maintain strength at elevated temperature. For example, an iron containing 0.4% Mn and 0.017% P had a limiting creep strength of only 8500 psi at 800 F. Optimum creep resistance is obtained with molybdenum alloyed iron.

Corrosion Resistance. In atmospheric corrosion tests nodular iron is similar to gray iron.

Physical Properties of nodular iron are listed in Table IV.

Application. Current uses of nodular iron based on strength and toughness, wear resistance, pressure tightness and heat resistance, include the following, by industries.

Aeronautical—Jet-engine burner support rings and jet-engine mounts. **Agricultural**—Tractor and implement parts. **Aluminum**—Pouring troughs. **Automotive and Diesel**—Crankshafts, pistons and cylinder heads. **Cement**—Kiln girth-gears and pinions. **Electrical**—Fittings, explosion-proof switch boxes, motor frames, end plates, and circuit-breaker parts. **Glass**—Molds and plungers. **Heavy Machinery**—Forging hammer anvils, cylinders, guides, control levers; press crowns, gears, and die shoes on heavy presses.

Marine—Tanker piping, compressor shells, staging clamps, and anchor-chain connection links. **Mining**—Hoist drums, drive pulleys, flywheels, elevator buckets, elevator-car guide brackets, sintering grates and drag-line gears. **Paper and Pulp**—Anti-deflection, calendar and suction rolls; pulp-dehydrator conveyor screws and cages; press swing-arms and beater drive-gears. **Petroleum**—Bubble caps, butane valve bodies, natural-gas line valves and pressure reducers, walking-beam center bearings and compressors. **Steel Mill**—Work rolls, table rolls and bearings, cooling-bed lifter bars, straightening screws for tubing, furnace doors, heat treating car-wheel bearings, coke-quenching car doors and plates. **Tool and Die**—Wrenches, levers, handles, clamp frames, lathe face-plates, chuck bodies, miscellaneous dies for shaping steel, aluminum, brass, bronze and titanium.

Table IV. Physical Properties of Nodular Iron

Property	Grade 80-60-03	Grade 60-45-10
Electrical Resistivity		
Microhm-cm at 73.4 F (23.0 C)		
2.5% Si	57.8	
3.1% Si	68.0	66.5
4.0% Si	72.7	
Magnetic Properties (3.1% Si in Iron)		
Peak induction, B = 10,000 gauss		
Peak H, oersteds	30.0	8.0
Residual Br, gauss	100.0	6000.0
Coercive force, Hc, oersteds	6.6	1.7
Hysteresis loss, w-sec./cycle, lb	0.1234	0.0348
Same for B = 15,000 gauss		
Peak H	244.0	156.0
Residual Br	6200.0	6200.0
Coercive force	7.5	2.0
Hysteresis loss	0.2009	0.0439
Maximum permeability		
For B = 3700 gauss	470.0	
For B = 5600 gauss		1780.
Thermal Properties		
Conductivity, cal./sq cm. cm. ⁻¹ /°C/sec	0.0741	0.0825
Expansion Coefficient, in./in./°F, both grades		
68 to 212 F	6.0 to 6.4×10^{-6}	
68 to 392 F	6.5 to 6.8×10^{-6}	
68 to 752 F	7.2 to 7.3×10^{-6}	
68 to 1112 F	7.5 $\times 10^{-6}$	

Damping capacity is between those of cast iron and mild steel; density, lb per cu in., 0.257; lb per cu ft, 444; melting range, 2050 to 2150 F; specific gravity, 7.1.

Applications of Aluminum and Aluminum Alloys

By the ASM Committee on Aluminum

THIS ARTICLE supplements the 1948 Metals Handbook by summarizing briefly the main developments in the aluminum industry since 1948 and by describing in more detail the applications of aluminum in the principal consuming industries.

Immediately following this article, property data are presented for six aluminum alloys that have gained major industrial importance since 1948. Briefe tabulations are given for 14 additional commercial alloys.

Compositions, properties and heat treatments of all alloys referred to in this Supplement are given either on pages 811 to 840 of the 1948 Handbook

or pages 60 to 63 here. Temper designations are defined on pages 808 and 809 of the 1948 Handbook.

1948 to 1953

Production of aluminum in 1953 was the greatest ever recorded. Trends are defined in Fig. 1 and Table I.

Bauxite mines have been opened in Jamaica to supplement domestic and South American supplies. Additional bauxite reserves have been examined in Haiti and arrangements completed for their development. With few exceptions, new reduction facilities have employed natural gas or lignite for

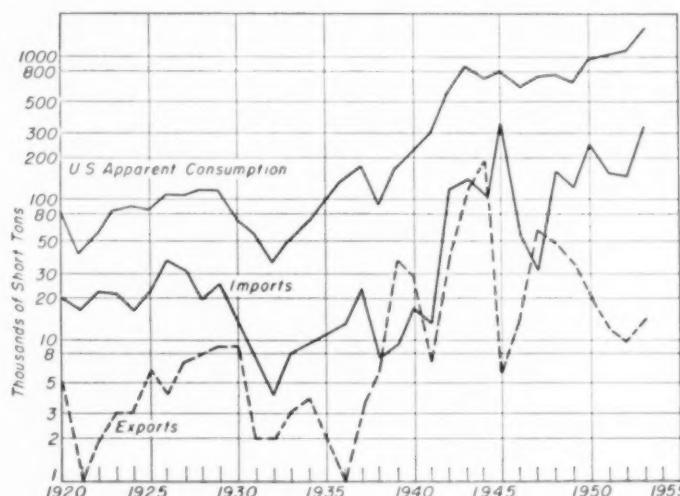


Fig. 1. Trends in Imports, Exports and Apparent Consumption of Aluminum, 1920 to 1953

Subdivisions	Page
Aircraft	53
Automotive	55
Railroad	56
Marine	56
Electrical	57
Appliances	58
Furniture	58
Construction	58
Chemical	59
Miscellaneous	59
Properties	
Al - 1.2 Mn - 1.0 Mg	60
Al - 1.2 Mg	61
Al - 0.7 Mg - 0.4 Si	61
Al - 9 Si - 3.5 Cu - 0.8 Mg - 0.8 Ni	62
Al - 10.0 Cu - 4.0 Si - 0.3 Mg	62
Al - 3.8 Mg - 1.8 Si	62
Other Alloys	63

power generation. Alumina and reduction plants located in the Louisiana and Texas region are close to natural fuel sources, and the overland shipment of both bauxite and alumina is reduced to a minimum. The principal advance in reduction technique has been the trend to the Söderberg continuous electrode.

Notable progress has been made in large extruded and forged shapes. Integrally stiffened shapes produced by

Table I. Aluminum Consumption, 1953
(See also Table, page 763, 1948 Handbook)

Transportation (land, sea, air)	28%
(Automotive, 12%)	
Appliances	13
Electrical and communications	11
(Conductors, 5%)	
Construction and building materials	18
Chemicals and paint	2
Machinery (nonelectrical)	12
Containers and packaging	4
Ferrous and nonferrous metallurgy	5
(Destructive uses)	
Miscellaneous	7

extrusion, forging and rolling have permitted simplified fabrication, higher strength-weight ratios and reduced cost. The benefits of integrally stiffened products are closely allied to newly developed straightening techniques of high precision and to specialized machine tools for shaping large aircraft components.

Close-tolerance castings produced by investment methods (both plaster and "lost wax" casting) have increased in use since 1948.

Continuous roll forming and welding equipment now produces thin-wall tube at lower cost than methods previously employed. Clad pipe is as easy to make as bare pipe, and the machine is adaptable to the entire range of most useful sizes.

Aircraft Applications

Aluminum is used in every segment of the aircraft industry—in airframes, engines, propellers and accessories. Virtually all commercially available aluminum alloys are utilized.

Nominal properties of the most used aluminum alloys are tabulated in great detail in the 1948 Metals Handbook, pages 810 to 840. Minimum values for use in aircraft design are published in:

Supplements the Aluminum Section of the 1948 ASM Metals Handbook, pages 761 to 840

- 1 Government specifications, as identified by item A4 in each of the property tabulations on Handbook pages 810 to 840
- 2 The Aeronautical Materials Specifications (SAE)
- 3 Bulletin ANC-5, "Strength of Metal Aircraft Elements", Subcommittee on Air Force-Navy-Civil Aircraft Design Criteria of the Munitions Board Aircraft Committee, U. S. Govt Printing Office, June 1951

Most of the nominal values for mechanical properties given in the 1948 Handbook are 10 to 15% higher than the minimum guaranteed values listed in the above publications.

Properties at Elevated Temperature. Aluminum alloys are used in aircraft structures up to 500 F. Such temperatures may be encountered (during flight) in engine components, heater ducts and areas where engine exhaust impinges, or from aerodynamic heating.

The elevated-temperature properties tabulated on Handbook pages 810 to

840 are the lowest strengths obtained during 10,000-hr holding at testing temperature. These numbers have little significance to the aeronautical design engineer except to give an indication of general trends. The results of creep-rupture and short-time elevated-temperature tests are more useful. Such data for clad 24S-T3 and 75S-T6 are presented in Fig. 2, for the usual testing rates of about 0.002 in. per in. per min, or approximately 20,000 psi per min. At higher rates, up to 100,000 psi per sec (6,000,000 psi per min), marked increases in properties are observed for some alloys. The increases in yield strength at 500 F when 24S-T3 and 75S-T6 are tested at 1000 psi per sec and 100,000 psi per sec are 12.9 and 23.3%, respectively. (Battelle Memorial Inst Pub G-1273, 1950.) Fatigue strength follows tensile strength.

Low-Temperature Properties. All aircraft should be designed for operation at -65 F; where liquefied gases are used as propellants, temperatures as low as -300 F are encountered. For these temperatures, almost any aluminum alloy can be used. Yield strength, tensile strength and modulus of elasticity usually show a substantial increase with decreasing temperatures; elongation and impact strength remain constant or decrease slightly. Typical data are given on Handbook pages 212 and 213. Additional information is available in "Literature Survey on the Low-Temperature Properties of Metals", by A. E. White and C. A. Siebert, Edwards Bros, Ann Arbor, Mich, 1947, and "Mechanical Properties of Metal at Low Temperatures", Nat Bur Stds, Circ 520, 1952.

Corrosion Resistance is important for many aeronautical applications; it may be the primary design requirement, as in containers for fuming nitric acid, or a secondary attribute, as when resistance to salt water corrosion is needed for shipboard aircraft. The basic theory and corrosion behavior of aluminum alloys are described on Handbook pages 791 to 797.

White fuming nitric acid, a common fuel for rocket motors, is usually contained in 2S alloy for storage and handling on the ground; in flight, 61S-T6 is used. Corrosion rates are given in Table II.

Increased resistance to salt water corrosion and other atmospheres is secured through the use of clad alloys or anodic coatings. The exterior of aircraft exposed to salt water environment is usually fabricated from clad alloys. Anodized bare stock successfully resists corrosion when only occasional salt water exposure is encountered. In these applications, the corrosion resistance may also be improved by organic finishes.

Water storage tanks are often made

Table II. Corrosion of Aluminum Alloys in White Fuming Nitric Acid

Alloy	Room Temperature	Corrosion Rate, in per yr	
		160 F	0.028
2S-O	0.000048	0.028	0.028
14S-T6	0.000036	0.034	0.034
24S-T6	0.000012	0.132	0.132
52S-O	0.000012	0.078	0.078
52S-H34	0.000012	0.036	0.036
61S-O	0.000016	0.032	0.032
61S-T6	0.000012	0.039	0.039

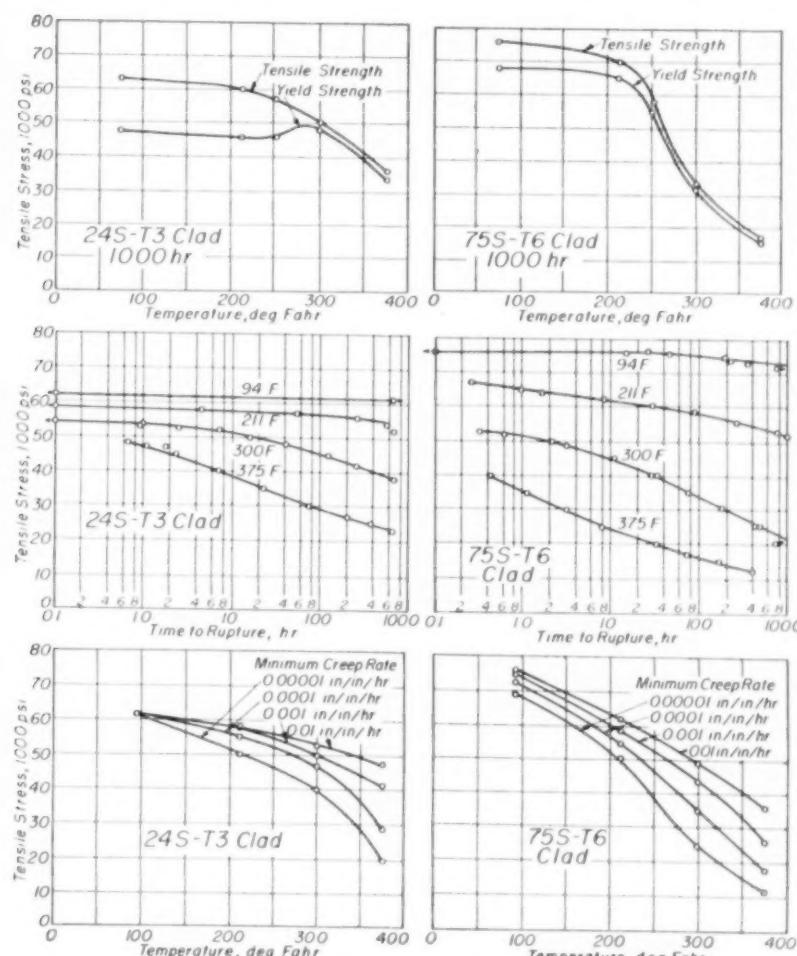


Fig. 2. Effect of Temperature on Tensile Properties of Clad 24S-T3 and Clad 75S-T6 Sheet 0.040 In. Thick [A. E. Flanagan, L. F. Tedson and J. E. Dorn, Trans AIME, 171, 213 (1947)]

Table III. Minimum Specification Values for Aluminum Alloy Hand Forgings
(Abridged from AMS 4135 and 4139)

Cross Sectional Area, sq in.	Longitudinal			Long Transverse		
	Yield Strength, psi	Tensile Strength, psi	Elong. % in 4D	Yield Strength, psi	Tensile Strength, psi	Elong. % in 4D
14S-T6 Alloy						
To 16	55,000	65,000	10.0	55,000	62,000	4.0
16 to 36	53,000	65,000	9.0	53,000	62,000	3.0
36 to 144	50,000	62,000	7.0	50,000	59,000	2.5
144 to 256	48,000	60,000	5.0	48,000	57,000	1.5
75S-T6 Alloy						
to 16	62,000	73,000	8.0	61,000	73,000	3.0
16 to 36	59,000	71,000	6.0	58,000	69,000	2.0
36 to 144	58,000	69,000	3.0	56,000	67,000	1.0

of clad 61S to improve resistance to pitting corrosion and to match the color of surrounding structural elements of clad 24S and 75S in commercial transports.

Fabrication. The first requirement of any aircraft component is high-quality workmanship. Deep scratches, dents, undercuts and similar defects accelerate fatigue failures. To reduce handling defects, most clad products are coated with a strippable protective plastic film or "shop coat".

Alloy A17S rivets driven cold in the fully heat treated condition are used extensively. 17S and 24S rivets of higher shear strength must be driven within 1 to 2 hr after quenching or refrigerated until used. They are used only where absolutely necessary because of the added difficulty in driving.

Inert-gas-shielded tungsten-arc welding is supplanting gas welding. Advantages are higher welding speed and elimination of flux with its attendant removal problems. Control of the torch, for delicate work, is equal to that of gas welding. The welding current is usually as with high-frequency stabilization; a foot control for amperage has proved very useful, especially in eliminating craters when stopping. Inert-gas-shielded welding with a consumable electrode is gaining favor rapidly on thicknesses over $\frac{1}{4}$ in.

In aeronautical applications, alloys high in copper and zinc are not fusion welded because of hot cracking and impairment of corrosion resistance. Thus, two of the most widely used alloys, 24S and 75S, are not considered weldable. However, the alloy 61S is satisfactorily weldable and can be heat treated to fairly high strength levels (45,000 psi tensile strength). In one application, 61S-T4 is welded by inert-gas-shielded tungsten arc at a speed sufficient to minimize heat effects adjacent to the weld so that, after aging the completed structure to the T6 condition, joint efficiencies of 90% can be realized. These high stress levels can be attained also by welding the SO material and subsequently heat treating it to the T6 condition.

Resistance welding is used extensively and is applicable to 24S and 75S. High quality requirements can be met in production by careful pre-cleaning and correct machine settings. Spots, voids, cracks, misshaped nuggets, burn-through, and excessive or insufficient penetration of nugget are all rejectable defects in aircraft-quality spot welds.

Alloys Used. The properties and fabrication characteristics described in the preceding paragraphs and in the 1948 Handbook are the significant factors leading to selection of aluminum

alloys for a wide variety of aircraft applications. Many of these applications are contained in the following list of typical parts, alloys and tempers:

Engine crankcases—A51S-T6
Engine cylinder heads—B18S-T6 or -T72 (if forged); 142-T77 (if cast)
Engine cylinder-barrel muff—A51S-T6
Engine baffles and deflectors—24S-T3
Engine pistons—32S-T6 or 18S-T61
Engine oil lines and push-rod cover tubes—24S-T3
Engine oil pumps—61S-T6
Engine supercharger impellers—14S-T6, 25S-T6
Engine castings in general—355-T6 or -T71; 195-T4 or -T6, 356-T6
Helicopter hubs—14S-T6
Helicopter rotor skins—24S-T4
Airplane skins and cowls—24S-T4, 75S-T6
Aircraft wing spars and attachment forgings—14S-T6, 75S-T6
Water tanks—61S-T6 or clad 61S-T6
Hydraulic line tubing—24S-T3, 52S-O, 61S-T4 or -T6
Rivets—A17S-T4, 17S-T4, 14S-T4 and 24S-T4
Control brackets, pulleys—195-T6, 356-T6, 355-T6, or 40E
Instrument cases—218 and 380 die castings
Spun or cast pressure receptacles—3S-O, 43S-O
Name plates—2S-O, 3S-O

Standard Forms. Aluminum and aluminum alloys are available in virtually any form or shape. Standard sheet sizes are 48 to 60 in. by 144 in. but sheets up to 120 in. wide and 360 in. long are available. Bars and extrusions are commonly stocked in 12 to 20-ft lengths, with longer products

available from the mills. Integrally stiffened or rolled tapered skins, large extrusions and press forgings, impact extrusions and precision castings can also be purchased now.

Hand Forgings. Hand or smith forgings are simple geometric shapes such as rectangles, cylinders and disks, or moderately contoured variations of these. They are produced on flat or contoured dies with blacksmith tools. These forgings fill a frequent need in the aircraft industry when a few pieces are required for prototype designs and the expense and time required to make impression dies cannot be justified.

Forgings up to 1000 lb are made regularly, those between 1000 and 2000 lb are less common, and pieces over 2000 lb are special items. Properties are lower in larger forgings (Table III).

Before solution treatment, 75S forgings should be reduced to 3 in. or less in thickness, if necessary by rough machining. Sections more than 3 in. thick may have lower strength than shown in the table.

Large Closed-Die Forgings. To produce parts of the greater size and complexity indicated by design forecasts, a "heavy press program" was initiated by the Air Force, and limited production was begun in 1948. Two hydraulic forging presses of about 18,000-ton capacity are currently operating and presses of 35,000 and 50,000 tons are under construction.

Forgings with a projected area of 1000 sq in. perpendicular to the parting plane are being made on the 18,000-ton presses, provided webs are not too thin. Larger chunky parts weighing up to 700 lb and simple T-section spars up to 14 ft long have been made successfully in production quantities. Figure 3 and Table IV show test bar locations and properties of a typical production forging.

Large Extrusions. Several large extrusion presses, sponsored and owned by the Air Force, are under construction; one in service has a capacity of 14,000 tons, nearly three times as large as any previously used in the U.S. It will produce shapes which may be circumscribed by a circle of 23-in. diam (Table V). Ingots up to 29-in. diam and 70 in. long, weighing up to 2500 lb can be extruded.

Larger presses will not only add to the size of sections, but the increased extrusion pressure will permit greater

Table IV. Typical Tensile Properties at Eleven Locations of the Production Forging (Alloy 14S-T6) Shown in Fig. 3

Test Location	Tensile Strength, psi			Yield Strength, psi	Elongation, %
	Longitudinal				
8C	68,000			60,000	11.0
19TCB	69,000			61,000	9.0
28TCB	70,000			63,000	10.0
Transverse					
16TC	68,000			62,000	5.0
25TC	67,000			61,000	3.0
34TCB	65,000			58,000	3.0
37C	68,000			62,000	8.0
Vertical					
1	65,000			60,000	1.5
18V	64,000			59,000	3.0
27V	63,000			59,000	2.0
33V	64,000			57,000	5.0

Longitudinal—axis of specimen parallel to grain flow; transverse—axis of specimen perpendicular to grain flow; vertical—axis of specimen perpendicular to grain flow and to the parting plane of the forging

intricacy in the design of smaller shapes. In addition, they should produce high-quality forging stock in sizes greater than now available and should present new opportunities for combinations of extrusion and forging.

Mechanical property data for the largest extruded sections are not yet available. Information on the design, construction and operation of the presses is given in a series of papers, "Symposium on Heavy Presses for Light Metal Forgings and Extrusions", Trans ASME, 75, 1483-1533 (Nov 1953).

Automotive Applications

The use of aluminum in the automotive industry dates back almost to the beginning of the motor car era. Aluminum sand castings were used extensively for flywheel and rear-axle housings, transmission cases, crankcases, clutch components, oil pans and other parts. In 1903 an aluminum body was adopted by the Pierce-Arrow, Franklin, Peerless and Jordan. Reasons for the use of aluminum in this early period were the ratio of weight to horsepower, tire limitations, and manufacturing problems such as materials handling and machinability.

The use of aluminum began to decrease as car production increased and competition became keener. Manufacturers resorted to lower-priced ferrous alloys. Present-day use of aluminum in passenger cars and in a large percentage of commercial trucks is limited to a few specific items. Approximately 65% of these vehicles contain a maximum of 15 lb of aluminum each; 35% use a maximum of 80 lb.

Truck manufacturers are unable to justify the use of higher-cost aluminum in high-production units. The full advantage of aluminum wheels, wheel hubs, axle housings, bodies and other items is realized only in specialized trucks.

The bus field is entirely different; 15 to 25% of the total weight of each vehicle is aluminum. Light weight is absolutely essential in large buses to meet legal weight limits. Aluminum permits more economical design and increases the efficiency of tires, brakes, axles and springs.

Table V. Minimum Section Thicknesses Available from 14,000-Ton Extrusion Press

Diameter of Circumscribing Circle, in.	Minimum Thickness of Solid Shapes, in.		
	61 S & 62 S	14 S	24 S & 75 S
To 13	0.109	0.125	0.156
13 to 16	0.125	0.156	0.187
16 to 19	0.140	0.171	0.250
19 to 23	0.156	0.187	0.357

Aluminum Alloys for Cars and Trucks.

Although aluminum pistons have been used in some automotive engines for many years, it was only during 1954 that 100% conversion was reached. This was part of the recent trend to higher speeds and higher-compression engines, in which the light weight and good thermal conductivity of aluminum pistons play an important part.

Pistons are cast in permanent molds from either A132 or D132 alloy with the latter predominant throughout the industry because of its lower cost. D132 has lower silicon and nickel and higher copper content; it also has better castability, which accounts for its price advantage. Pistons receive the T551 heat treatment, which increases hardness and stabilizes the structure. The finish-machined piston can either be anodized or tin plated for improved anti-scruff properties.

The largest usage of aluminum per car is in the torque converter type of automatic transmission. The most common method of producing torque converter parts is plaster casting, because of its advantages for thin and intricate sections, close tolerances and extremely smooth surfaces. A combination of permanent, plaster and shell molding is being utilized by one source in making the turbine at appreciably reduced cost. Alloys used are of either the 319 or 355 type, with or without heat treatment. To reduce cost further one manufacturer is die casting the stator in 380 alloy with good results.

Camshaft timing gears for a large number of truck engines are permanent-mold cast from either D132 or 355. The D132 alloy, somewhat more costly, receives only an aging treat-

ment, which develops a uniform hardness of 90 to 115 Brinell, and has better wear resistance. Alloy 355 is solution treated and aged to between 75 and 95 Brinell.

Die-cast brake-cylinder pistons are being used throughout the industry. One car has die-cast aluminum in valve rocker-shaft brackets for compensation of temperature effects; another manufacturer has developed die castings for carburetor and fuel pump bodies. A die-cast clutch housing is currently being installed by a third company. This item, weighing 4.5 lb, replaced a gray iron casting weighing 17 lb. 380 alloy is usually specified for these applications because of its castability and machinability.

In investigating the many possible uses for aluminum die castings, car manufacturers proceed on the premise that successful use depends on proper designing for aluminum rather than mere substitution for other metals. Die casting has several well recognized qualities such as its high production rate and lower assembly and unit costs. Die castings have recently been found capable of serving as functional parts carrying moderately high loads, as in the clutch housing just mentioned.

A small amount of 38, plain or embossed, is used in the car body, principally for door sill strips. Its major advantage is corrosion resistance without costly surface coatings. Reflectors, headlamp housings, name plates and instrument panels also are fabricated from 28 or 38. There is limited but increasing use of aluminum strip and extrusions for trim and upper door frames.

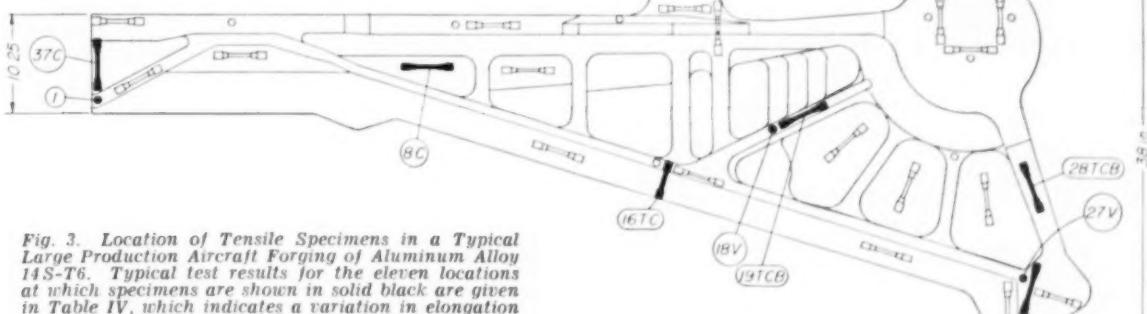
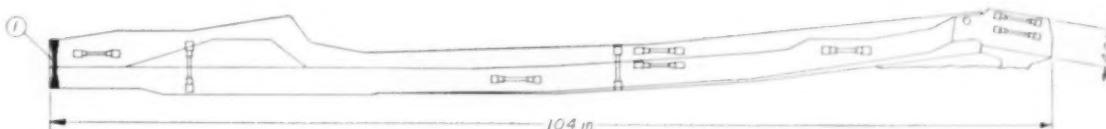


Fig. 3. Location of Tensile Specimens in a Typical Large Production Aircraft Forging of Aluminum Alloy 14S-T6. Typical test results for the eleven locations at which specimens are shown in solid black are given in Table IV, which indicates a variation in elongation from 1.5% at location 1 (vertical direction), with 11.0% at location 8C (longitudinal direction), with both specimens having the same yield strength.



Aluminum Alloys

Trailers. Trailers use as much as 3000 lb of aluminum in an 8000-lb unit. The initial cost of the trailer is increased but in many operations the profit from greater pay load more than offsets initial cost.

Principal members such as floor support channels, cross members and floor plates are made from clad 61S-T6, 62S-T6 and 24S-T3 alloys. Secondary members like side posts and roof bows are also made from these alloys. Side panels are usually made from clad 24S-T3 and 61S-T6 sheet, and roof panels from either the clad material or 3S-H14 alloy. Drip trough, moldings and trim are extruded from 63S-T5 alloy. A17S-T4 or 53S-T6 rivets are used in assembly.

Cast wheels, gear boxes, corner castings and support brackets are made from 355 or 356 in the T6 or T71 condition, with some special applications of 40E or 220-T4. Forged wheels are made from 24S-T3 alloy in both disk and spoke designs.

Buses. Approximately 5000 lb of aluminum is used in a 20,000-lb bus, with sheet and plate 50% of this amount, extrusions and sand castings each 20% and other forms 10%.

Typical uses for aluminum in bus construction, both gasoline and diesel engine types, are as follows:

Wrought Aluminum

2S-O—Name plates and foil faced insulation.

3S-O, -F, and -H14—Refrigerant condenser and evaporator units, extrusions for trim

11S-T3—Screw machine parts

14S-T6—Forgings for wheel hubs and special air-cylinder pistons

52S-O, -H32 and -H34—Primarily used for skin sheet exterior and interior, heat deflector shields, modesty panels, wheel housings, air ducts. The three tempers cover applications from flat to deep drawn sections.

53S-T6 and A17S-T4—Rivets

61S-T6—Sheet and plate for highly stressed areas for exterior panels and other locations where strength is the primary consideration

61S-T6 and 62S-T6—Extrusions for structural parts like post and roof sections, braces, struts, angles and floor supports

63S-T42 and -T5—Extrusions for nonstructural applications, mainly moldings and trim.

Aluminum Castings

40E and 220-T4—Spring brackets, air suspension support, brake-rod support bracket, door control handle, door hinges, steering housing, generator cradle and bumper guards

43—Stepwell tread plates with grit, water inlet and outlet elbows, thin complex sizable castings requiring slight alignment in assembly

A132-T551 and D132-T5—Engine pistons, camshaft gear, special oil seal retainers

195-T6—Brackets. (Alloy is being superseded by 356-T71, 40E and 220-T4.)

F214—Headlight and directional light castings, rear view mirror frame and bracket, front and rear-end trim castings, decorative parts—polished and anodized

319 as cast, -T51 or -T6—Blower housing and rotors, water inlet manifold, air cleaner base and cover, oil pans, radiator tanks, air intake manifold, connecting flanges and couplings, spacers

355 or 356, -T6 or -T71—Transmission cases, flywheel housing, air cylinder cases, low-inertia flywheel and clutch-drive plates, brake shoes and many types of support brackets

380—Grab rail support brackets, valve body cases, governor housing, compartment door handles

The alloy selections for the various applications follow closely the recommendations given on Handbook pages 810 to 840.

Aluminum Bearings. Two types of aluminum bearings are used in some medium and heavy-duty engines for connecting-rod and main bearings. One type bearing, alloy 750, containing 6.5% Sn, 1.0% Cu and 1.0% Ni, normally a permanent mold casting, is used in

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heavy-duty diesel engines, with or without some modifications of composition. The other is a composite type, incorporating an aluminum bearing alloy in strip form, containing cadmium and silicon, which is bonded to steel and electroplated with babbitt. This latter type is used in both gasoline and diesel engines for trucks and buses. (See also pages 754 and 840, 1948 Handbook.)

Fabrication. Riveting is the main joining process used in all structural applications. Both A17S-T4 and 53S-T6 rivets are used by bus manufacturers; one company prefers the more expensive 53S-T6 rivet because of its excellent corrosion compatibility with 52S, 61S and 62S.

The three major welding processes used in bus construction are spot welding, inert-arc, and gas welding. Only nonstructural assemblies are joined by welding; these include parts such as

battery trays, panel stiffeners, wheel housings and window reveals.

Painting and Anodizing. Joints between aluminum and ferrous parts must be protected from galvanic corrosion by painting prior to assembly. Sealers containing chromate inhibitors are used in joints where additional protection is necessary. In painting, a phosphate conditioning treatment is first used to prepare the surface, followed by zinc chromate primer and finally synthetic enamel finish. Anodic coatings are used extensively as a finish, both exterior and interior, for both decoration and protection.

Railroad Applications

Aluminum is used in diversified railroad applications on motive power, freight and passenger cars and maintenance-of-way equipment.

Passenger Cars. Practically every passenger car built today uses some aluminum for items such as interior finish and trim, window sash, baggage racks, lighting fixtures, furniture and other items. Alloys are usually 3S sheet, 63S-T5 extrusions and tubing, and 61S-T6 extruded shapes. These items save weight and maintenance.

Car bodies are designed in accordance with specifications of the Association of American Railroads, which also dictates to some degree the type of aluminum alloy that may be used. Structural shapes are either rolled or extruded 14S-T4 and 61S-T6. Roof and side sheets are clad 24S-T3. Formed or secondarily stressed sheet parts are 52S-H34.

Tank-Car Tanks. Aluminum tank cars were first introduced in 1928 and there are now nearly 2000 in service. These are built to specifications of either the Association of American Railroads or the Interstate Commerce Commission, depending on the commodity to be handled.

Most tanks are of welded construction using 99.6% aluminum and alloys 2S, 3S, 52S, A54S and 61S, in various tempers.

Commodities handled are restricted to those which are adversely affected by other metals and lining materials, and include glacial acetic acid, nylon salts, formaldehyde, water-white rosin, fatty acids, glycerin, hydrogen peroxide, ethyl acetate, polyvinyl acetate, stearic acid, oleic acid, naphthenic acid, trichlorobenzene, concentrated nitric acid and nitrogen fertilizer solutions. Some of these materials can be handled only in certain concentrations and degrees of contamination with other compounds. The list will probably be expanded as the need arises for bulk handling of other liquids.

Other Freight Cars. Aluminum hopper cars, box cars and refrigerator cars are undergoing long-time performance tests and are still considered experimental by the users. Alloy 61S-T6 is used for all structural members and 52S and 61S-T6 for sheets.

Marine Applications

Aluminum alloys were used in marine craft as early as 1891 but the alloys then available were handicapped by poor resistance to corrosion. Since about 1930, improved alloys have been used increasingly, and today the following components, including main strength members, commonly utilize

aluminum alloys: hulls, deckhouses, stack enclosures, hatch covers, windows, air ports, accommodation ladders, gangways, bulkheads, deck plate, ventilation equipment, life saving equipment, furniture, hardware and architectural trim.

Alloys in Use. The following combinations of alloy, temper and form account for most of the aluminum applications in marine service: 3S sheet, plate and extrusions in the F and intermediate tempers; 52S-H32 sheet and plate; 61S-T6 sheet, plate and structural shapes; 63S-T6 architectural trim; 43, 214 and some 356 castings. Rivet material is 53S in tempers T6, T61, T41 and 61S in tempers T6 and T31.

The corrosion-resistant aluminum alloys in current use permit designs which save about 50% of the weight of similar designs in steel. Substantial savings of weight in deckhouses and top-side equipment permit lighter supporting structures. The accumulative savings in weight improve the stability of the vessel and allow the beam to be decreased. For comparable speeds, the lighter, narrower craft will require a smaller power plant and will burn less fuel. Consequently, one pound of weight saved by the use of lighter structures or equipment frequently integrates to an over-all savings on the order of three pounds. Aluminum also saves on marine maintenance.

The low values of modulus of elasticity for aluminum alloys offer advantages in structures erected on a steel hull. Flexure of the steel hull results in low stresses in an aluminum superstructure as compared with the stresses induced in a similar steel structure. Consequently, long continuous aluminum deckhouses can be built without expansion joints, thus eliminating a serious maintenance problem.

Die-cast alloy 13 predominates in outboard motor structural parts and housings subject to continuous immersion or to frequent wetting. Die castings with a nominal composition of 9.7% Si, 23% Cu and 0.6% Fe are also used for motor hoods, shrouds and miscellaneous parts subject to less severe corrosive exposures. Wrought alloy 3S monopolizes integral gas tanks which are drawn from sheet stock.

Hull construction in most small craft such as outboard motor boats, row boats and canoes, including those designed for operation in fresh water, is shifting to 61S-T4 or -T6 extrusions or sheet. A small amount of 3S is used as casing for built-in safety buoys.

Prevention of Galvanic Corrosion. Aluminum alloys should be either cathodically protected or electrically insulated from dissimilar metals unless contact between aluminum alloys and steel or other cathodic metals can be avoided, especially below water line. Any good quality caulking or gasket compound inserted between the dissimilar metals will provide durable joints with adequate electrical insulation, particularly if the facing surfaces have been painted with a zinc chromate primer. Faying surfaces of dissimilar metals subject to frequent wetting aboard ship or in other marine atmospheres require the same type of protection as do aluminum alloy contacts with wet wood or other absorptive board materials.

Methods of Fabrication. Riveted construction is generally favored. Shop procedure and fabrication of aluminum

alloys follow well established practices similar to steel practices except that somewhat greater care is required. More detailed fabricating practices and shop procedures are given in the references.

Recently the U. S. Navy has pioneered the welding of aluminum for marine structures, using semi-automatic inert-gas-shielded arc welding with consumable electrodes. Welding greatly reduces the cost of fabrication; on some structures the savings have amounted to as much as two-thirds of the cost of fabricating similar riveted units. Progress in fabricating welded structures has focused attention on the aluminum-magnesium alloys containing more than 2.5% Mg.

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Electrical Applications

The first significant application of aluminum in the American electrical industry occurred in 1898 with the use of stranded 99.5% aluminum wire as an overhead, high-voltage transmission line. Over 90% of the transmission lines in this country now employ either aluminum cable or steel-reinforced aluminum cable, which was introduced in 1909. About 15% of all distribution lines also utilize aluminum conductors.

In 1953, the electrical industry manufactured an estimated 644 million aluminum foil capacitors from about 6.5 million pounds of foil.

Alloys for Conductors. Electric conductor or EC alloy accounts for all but a minor proportion of the aluminum now being used as conductor metal in the U. S. EC contains 99.45% min Al, with closely controlled impurities and trace additions of copper and boron. Specifications are given in ASTM B233-52, B230-53T and B262-52T.

The extensive use of EC alloy rests on a fortuitous combination of low cost, high electrical conductivity, adequate mechanical strength, low specific gravity and excellent resistance to corrosion. Minimum conductivity of 61% of the International Annealed Copper Standard (IACS) and from 23,500 to 29,000 psi tensile strength, depending on size, are readily maintained in commercial hard drawn EC wire. When compared with the IACS on a basis of mass instead of volume, minimum conductivity of hard drawn EC alloy is 201%.

Magnesium-silicide alloys are finding a growing use as 61S and 63S alloy bus bar and as "Cond-Al" alloy wire for service at slightly elevated temperatures. Cond-Al has a nominal composition of 0.10% Si, 0.45% Fe and 0.30% Mg. Additional details are available in Metal Progress for May 1953.

Aluminum for cable sheathing varies widely from high-purity commercial aluminum to alloys of the 3S type. Two methods are used: (1) extruding the sheath in final position and dimensions around the cable as it is fed through an axial orifice in the extrusion die, and (2) threading the cable through an oversized prefabricated tube and then squeezing the tube to final dimensions around the cable by tube reducers and draw dies.

Conductor accessories also vary widely from EC alloy to the heat treatable, high-strength wrought alloys and casting alloys such as 214 and 356.

EC Alloy Wire Conductors. Common forms of EC alloy conductors are single-wire and multiple-wire (stranded, bunched or rope layed). Both are used in overhead or other tensioned applications as well as in nontensioned insulated applications. The tensioned conductors employ EC wire in the H19 temper; nontensioned, H26.

Size for size, the d-c resistance of an EC aluminum conductor is 1.59 times the annealed copper value. For equivalent d-c resistance, an aluminum wire two AWG size numbers larger than a copper wire must be used. Nevertheless, as a result of the lower specific gravity of aluminum, an EC conductor weighs only about half as much as an equivalent copper conductor.

Current-carrying capacities for EC wire conductors are given in the Conductor Data Book of Kaiser Aluminum and Chemical Corp., 1954. Recently specified standard constructions for weatherproof type EC conductors, neutral supported service drops and secondary EC cables are given in ASA Specifications for Weather-Resistant Wire and Cable, Second Draft, June 20, 1952.

Aluminum Conductors, Steel Reinforced, consist of one or more layers of concentric-lay stranded EC alloy wire around a high-strength galvanized steel wire core which itself may be a single wire or a group of concentric-lay strands. ACSR design and materials are specified by ASTM B232-52T.

ACSR constructions are somewhat larger in diameter and far stronger than equivalent conductors employing only EC aluminum alloy. Electrical resistance is figured only on the aluminum cross section, whereas tensile strength is figured on the composite; the steel core provides 55 to 60% of the total strength.

ACSR constructions are used where great mechanical strength is advantageous. Their strength-to-weight ratio is usually about two times that of copper of equivalent d-c resistance. ACSR cables, therefore, permit longer spans and fewer poles or towers.

Characteristic data for commonly used ACSR types are given in the "Standard Handbook for Electrical Engineers," 8th ed, Tables 4-24 and 4-25.

Bus Bar Conductors. Commercial bus design in the U. S. utilizes four types of bus conductors: rectangular bar, solid round bar, tubular and structural shapes.

Aluminum Alloys

All types are supplied in EC alloy with tubular and structural shapes available in 61S and 63S also. Temper, alloy and shape availabilities are given in "Aluminum Bus Conductors", Aluminum Co. of America, 1948.

Motors and Generators. Aluminum has been used for many years for cast rotor windings and for several structural parts. The end rings and usually the cooling fans are pressure-cast integrally with the bars through the slots of the laminated core, from commercially pure aluminum ingot. The rotor thus formed stays permanently tight and quiet and has cost advantages.

Aluminum structural parts such as stator frames and end shields are sometimes economically die cast. Their corrosion resistance may be necessary in specific environments, for example, in motors for spinning rayon (aluminum salts do not stain the fibers). They are also found in aircraft generators where light weight is paramount.

EC aluminum has more recently been introduced for field coils on some of the d-c machines and for stator windings in some motors. "Cond-Al" alloy wire is now used in some of the extremely large turbo-generator field coils where high operating temperatures and centrifugal forces cause creep failures in EC alloy and other conductor wire.

Transformers. Aluminum has been adapted to the secondary coil windings in the magnetic-suspension type of constant-current transformer, to decrease weight and permit the coil to "float on magnetic suspension". In an application closely associated with transformers, it is being used for concrete reactors (devices to protect transformers from overloads) where aluminum conductors are cast in concrete.

Electronics applications where aluminum is used primarily because of its electrical characteristics include hollow shapes both cast and wrought in radar and sonar wave guides, copper-clad strips in printed circuits and other applications where weight is important, extruded shapes and punched sheet for radar antennas, extruded and roll formed tubing for television antennas, strips in lengths up to 300 ft for coiled line traps, drawn or impact-extruded cans for condensers and shields, and vaporized high-purity coatings inside cathode-ray tubes.

Examples where electrical properties other than magnetic are not dominant are chassis for electronic equipment, spun pressure receptacles for airborne equipment, etched nameplates and hardware such as bolts, screws and nuts. A closely associated use is 61S-T63 as a cell base for the deposition of selenium in the manufacture of selenium rectifiers.

Lighting. The use of 4S aluminum for lamp bases, because of high melting temperature, and other sheet alloys for sockets are two recent developments.

Capacitors. Aluminum, in the form of foil, dominates all other metals in the construction of capacitor electrodes. Dry electrolytic and non-electrolytic capacitors are the only two basic types of condensers in extensive commercial use today. Dry electrolytic capacitors usually employ two parallel coiled or wrapped aluminum foil ribbons as elec-

trodes. Paper wrapped into the coil mechanically separates the two ribbons. A glycol-borate paste, which is absorbed in the paper separators, functions as the operating electrolyte. In constructions designed for intermittent use in alternating circuits, both electrodes are anodized in a hot boric acid electrolyte, the thin anodic films constituting the dielectric element.

Only the anode foil is anodized in dry electrolytic assemblies intended for d-c applications. Anodized electrodes are invariably made in aluminum of 99.8% or greater purity, whereas the non-anodized electrodes usually utilize foil ribbons of 99.4% minimum purity. Prior to anodizing, the foil is usually but not always etched to increase the effective surface area. Containers for dry electrolytic capacitors may be either drawn or impact-extruded cans of 2S alloy.

Ordinary clean foil ribbons of 99.4% minimum purity usually serve as the electrodes in commercial nonelectrolytic capacitors. Oil-impregnated paper separates the electrodes and adjacent coils of the wrap. Nonelectrolytic, foil assemblies are packed in either aluminum alloy or steel cans.

Electrodes for variable air capacitors are usually made of 2S or 3S sheet in the intermediate tempers.

Electrical Appliances

The following properties of aluminum and its adaptability to all forms of fabrication have resulted in a broad usage in electrical appliances.

Weight. Household appliances such as vacuum cleaners, electric irons and portable food mixers are continually moved about by the housewife; hence, light weight is an attractive sales characteristic.

Low Fabricating Costs depend on several properties, including adaptability to die casting and low finishing costs because of a natural pleasing appearance and good corrosion resistance which eliminate the need for expensive finishing.

High Thermal Conductivity is the dominant factor governing its use in the electric range deep-well cooker pail and trivet, refrigerator evaporators, waffle iron grids, sandwich grills, electric-iron sole plates and other items.

Reflectivity of polished aluminum is desirable in such things as the heater box in automatic dryers, adjustable reflecting shelves in electric range ovens and reflectors under the resistance heating units in electric ranges.

Damping Capacity of aluminum has led to its use for electric fan parts. Aluminum carrier, hub and blades provide quieter operation.

Brazability. Aluminum is used for refrigerator and freezer evaporators because of its brazability, in addition to other favorable characteristics. 2S or 3S aluminum tubing is brazed to 3S embossed sheet, using aluminum-silicon alloy 713 for the braze metal. The tubing is placed on the embossed sheet over strips of brazing alloy with a suitable flux. The assembly is then furnace brazed, and the residual flux is removed by successive washes in boiling water, nitric acid, and cold water. The result is an evaporator with high thermal conductivity and efficiency, good corrosion resistance and low manufacturing cost.

Choice of Alloy and Finish. With the exception of a few permanent mold parts, practically all of the aluminum castings in electrical appliances are die cast. The most popular alloy is 380 because of its good castability, adequate mechanical properties and low cost.

Most of the die castings are internal functional parts and are used without any finish. Organic finishes are usually applied to die-cast parts exposed to view, such as housings for food mixers.

Wrought forms fabricated principally from sheet, tube, and wire are used in approximately the same quantities as die castings. The wrought alloys 2S, 3S, C57S, 50S, 52S and a few 63S extrusions are selected because of corrosion resistance, anodizing characteristics and excellent formability. C57S is outstanding in its anodizing characteristics and is used with a copper-colored, dyed anodized surface for trim on some electric ranges.

The natural colors which some of these alloys assume after anodizing are extremely important for food handling equipment. Applications include refrigerator vegetable pans, ice cube trays and wire shelves. The pans and trays are usually drawn from 3S; the separating partitions in the trays require greater yield strength and are made from alloys such as 52S. Wire shelves are sometimes made from 50S-H38, anodized after fabrication. In this application the full-hard wire is cold headed over extruded strips which form the borders.

An exception to the natural color anodized surface for food handling equipment occurs in waffle iron grids, which are given a silicone resinous finish to facilitate removal of the waffle.

Furniture

Light weight, low maintenance and attractive appearance are the principal advantages of aluminum in furniture.

For office chairs, the most commonly used alloy is 61S-T6 in the form of drawn tube (round, square or rectangular), sheet or bar. 63S-T5 extruded tube and special shapes are also used. Frequently the parts are formed in the annealed or partially heat treated tempers and subsequently heat treated and aged. Designs are generally based on the service requirements, although styling may dictate overdesign or inefficient sections. Fabrication is conventional; joining is usually by welding or brazing. Various finishing procedures are used, such as mechanical, anodic oxide coatings or paint finishes.

Tubular sections, usually round, are the most popular form of aluminum in lawn furniture. Resistance to corrosion is an added advantage. Designs are established by structural engineering practices, with some deviations for appearance requirements. Alloys principally used are 3S, 63S and 61S, the temper being selected by strength requirements and the degree of forming required. Conventional tube bending machines and mechanical joints are used. Finishing is usually by grinding and buffing, frequently followed by clear lacquers.

Construction Applications

Aluminum is being used increasingly in static structures such as buildings, bridges and towers. Because structural steel shapes and plate are substantially

lower in first cost, aluminum is used only where light weight or the cost of maintenance is a major consideration.

Design and Fabrication of aluminum static structures differ very little from the practices used with steel. The most common alloys are 61S-T6 and 14S-T6. Tensile strengths are in the range of structural carbon steel and low-alloy steel, respectively; the modulus of elasticity is one-third that of steel, requiring special attention to compression members; it also provides a cushion against shock loads and minor foundation misalignment. Conditions of repeated loading require special consideration; high temperatures reduce strength and raise ductility. Both strength and ductility are maintained or improved at sub-zero temperatures. Over 50% of the weight of small structures is saved; 75% or more may be possible in long-span or movable bridges. Substantial savings result in maintenance and in depreciation from atmospheric corrosion.

Forming, shearing, sawing, punching and drilling are readily accomplished on the same equipment used for fabricating structural steel. Since the structural aluminum alloys owe their strength to properly controlled heat treatment, hot forming must be done with caution, and sometimes reheat treatment is necessary. Burning or flame cutting should not be used. Special attention must be given to the strength requirements of welded areas because of the annealing effects.

Buildings. The most important aluminum applications to farm buildings have been corrugated or otherwise stiffened sheet products. Alloy 3S or similar compositions are employed, usually in the harder rolled tempers. Roofing, siding, ventilators and other components are made of similar materials.

The use of aluminum in industrial buildings has likewise been generally limited to portions exposed to weather. Roofing and siding are the most common applications; the alloys most used are 3S, 4S and 52S, either bare or clad. Door and window frames are usually formed of 63S-T5 extruded shapes. A few buildings have 61S-T6 framework to resist corrosive conditions within. Examples are greenhouses and locomotive round-houses.

Aluminum roofing, flashing, gutters and downspouts of 3S or 4S, preferably clad, are used in homes, hospitals, schools, commercial establishments and office buildings. Exterior walls may be either 63S-T5 extrusions or formed sheet, bare, anodically treated and painted, or enameled. In addition, many interior applications such as wiring, conduit, piping, ductwork, hardware and railings utilize aluminum in many forms and finishes.

Bridges. A great deal of aluminum is used in bridge accessories such as railings, lighting standards, traffic control towers and marking devices. Aluminum is economically feasible for bridges of extremely long span and for movable bridges of the bascule and vertical-lift types. Portable military bridges have been built in quantity.

Scaffolding, Ladders, electrical substation structures and others of the same general type utilize aluminum, chiefly in the form of structural and special extruded shapes. 61S-T6 is the most widely used alloy because of strength and resistance to corrosion

without paint. Specifications in Proc ASCE, 78, Separate 132 (May 1952), cover allowable stresses, design rules and fabrication procedures for 61S-T6 alloy in these applications.

Cranes, Conveyors and heavy-duty structures utilize smaller amounts of aluminum than the category just discussed. The most popular alloy in this field is 14S-T6. For information on allowable stresses and design rules for riveted heavy-duty structures of this kind, the reader may refer to Trans ASCE, 117, 1253 (1952).

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Structural Handbook, Aluminum Co. of America, 1948

Chemical Process Applications

In general, the aluminum alloys most suitable for use in the chemical process industries are the lowest in cost.

Petroleum. Aluminum tops are used on steel storage tanks and exteriors are painted with aluminum paint. An important benefit results from its high reflectivity. Temperatures of tank contents are kept low and evaporation of volatile constituents is greatly reduced. Equally important is the protection of exterior steel surfaces from atmospheric corrosion, and the interior surfaces from corrosive brines, sulfide gases and sulfur contained in the oil. Contamination of tank contents, caused by corrosion products dropping from sides and tops of unprotected steel tanks, is also eliminated.

All-aluminum pipe lines with welded joints are satisfactory carriers of both crude and refined products. Aluminum trailers and tank trucks have an additional advantage of light weight. Small field tanks are generally of 2S or 3S alloy; in larger tanks, where strength is more important, 61S is used.

Rubber. Aluminum resists all types of corrosion that occur in rubber processing, and is nonadhesive with all forms of rubber. Aluminum molding equipment without special surface preparation imparts a glossy finish to rubber products. Pen and pencil bodies, pipe stems, combs and battery cases are some products formed in such molds.

Sewage Disposal. The principal gaseous products of sewage decomposition (hydrogen sulfide, methane, carbon dioxide and nitrogen) have no appreciable action on 2S, 3S, 52S, 61S and 63S. These alloys also have satisfactory resistance to raw and partially treated sewage. Aluminum grit chamber wires, sluice gates, sludge equipment, rotary distributors and other plant items have proved satisfactory.

Explosives. The nonsparking characteristic of aluminum is of particular importance in explosive atmospheres. This safety consideration has been primarily responsible for the many mechanical handling devices made of aluminum for the explosives industry. Safety tools of aluminum have similar advantages. Storage facilities for nitroglycerin, guncotton and dynamite and evaporator pans and crystallization kettles for ammonium nitrate are usually made of aluminum. Air-conditioning equipment in explosives plants

utilizes aluminum construction almost exclusively.

Food. High-purity aluminum, 2S and 3S are used in large food processing equipment such as pressure cookers, pasteurizers, cheese and butter making equipment and in storage and shipping tanks for liquid foodstuffs.

General Chemicals. Strong oxidants (permanganates, peroxides, oxygen, nitric acid) are processed, stored and shipped in aluminum equipment. Sulfur, sulfuric acid, sulfides and sulfates are particularly well suited to processing in aluminum. The halogen gases, acids and salts are generally incompatible with aluminum; so are most carbonates, hydroxides and phosphates.

Designers of aluminum containers and equipment for the chemical industries should avoid features that entrap liquids and prevent complete drainage. Periodic thorough cleaning greatly increases the service life of equipment. Heavy metal contamination in otherwise noncorrosive substances will frequently cause severe local corrosion. Over-all corrosion will often be greatly accelerated by small amounts of water in normally anhydrous or highly concentrated materials.

Atomic Energy. Aluminum-jacketed fuel elements protect uranium from water corrosion, prevent the entry of fission products into the cooling water, transfer heat efficiently from uranium to water, and minimize parasitic capture of neutrons. Aluminum tanks are used in reactors to hold heavy water. One form of fuel element employs aluminum tubes closed at the bottom and containing a stack of uranium slugs. Uranium-aluminum alloys rolled into flat sheet and protected by high-purity aluminum cladding are another form of nuclear fuel. Shim controls made of cadmium plates, clad with aluminum, slide on aluminum scabbards in one type of reactor.

Brewing. In the brewing industry, 2S and high-purity aluminum have been used for highest corrosion resistance; higher-strength alloys have also been employed. Aluminum brew kettles, yeast tubs, culture tanks, fermenting tanks, storage tanks, coolers and barrels are typical uses. Aluminum does not impart taste or odor to beer, nor does it affect the growth of yeast or the fermentation process. High thermal efficiency is realized in aluminum brew kettles and other heating or cooling devices, and aluminum is highly resistant to the weak acids formed during fermentation. Shipping barrels are of both clad and unclad construction.

Miscellaneous Applications

Cost, formability and appearance are more significant in these applications than in most of those discussed above. The uses mentioned below do not include many that account for large consumption of aluminum, but they illustrate a variety which, in the aggregate, account for large tonnages.

Materials Handling Equipment. The food industry uses aluminum handling equipment more than other industries, because the metal is nontoxic, non-adsorptive, splinter-proof, does not harbor bacteria, and can be steam cleaned. High thermal conductivity results in economies when containers or conveyors must be moved in and

out of heated or refrigerated areas. The nonsparking property is invaluable in flour mills and other plants subject to fire and explosion hazards.

Corrosion resistance is important in shipping fragile merchandise, valuable chemicals and cosmetics. Large sealed, aluminum containers designed for either rail or truck shipments are used for chemicals not suited to bulk shipment in box cars or hopper cars. Other examples of handling equipment include: airplane baggage carts, wheelbarrows, hand shovels, pallets, dock boards, bakery cabinets, tipping slings, electric hoist housings, lift-truck parts, beverage cases, bread handling racks and liquid transfer pumps.

Coal Mine Machinery. The use of aluminum equipment in coal mines has increased in recent years; applications include cars, tubs and skips, roof props, nonsparking tools, portable jacklegs and shaking conveyors. Aluminum is resistant to the corrosive conditions generally associated with coal mines; the metal is self cleaning—wet coal will not stick to it—and it offers good resistance to abrasion, vibration, splitting and tearing.

Textile Equipment. Aluminum is used extensively in textile machinery and equipment in the form of extrusions, tube, sheet, castings and forgings. It is resistant to many corrosive agents encountered in textile mills and in the manufacture of yarns. High strength-weight ratio reduces inertia of high-speed machine parts. Permanent dimensional accuracy, with light weight, improves the dynamic balance of machine members running at high speeds and reduces vibration. Painting is usually unnecessary. Alloys include:

3S-H14 for card rolls;
3S-H18 for reed frames;

61S-T6 for card rolls, roving frames, ring rails, spindle rails, roller beams, brush holders, bobbins, drying poles, finishing equipment, heddle frames, sewing machine parts, beam barrels, lay beams and hand rails;

14S-T4 for card plates and flats, spinning drive cylinders, heddle frames, hosiery knitting machines, guide bar hangers and beam barrels;

63S-T5 for card rolls, roving frames, spindle rails, roller beams, spinning mules, lay beams, hand rails, cloth rolls, yarn trays, plant construction, batten beams, and lap rolls;

52S-H14 for separator blades;

53S-T4 for spinning buckets;

11S-T3 for tricot beams, spindles, spindle adaptor and spindle sheaths;

24S-T4 for bobbins and hosiery pre-boarding machines.

Portable Irrigation Pipe. 2 to 8 in. outside diameter, is extensively used for portable sprinkler irrigation systems. The aluminum pipe is extruded or drawn in 63S, or roll formed and welded from 4S, 50S and other alloys.

Jigs, Fixtures and Patterns. Thick cast or rolled aluminum plates and bars, precisely machined to high finish and flatness, are used for tools and dies. The plate is suitable for hydro-press form blocks, hydro-stretch form dies, jigs, fixtures and other tooling. It is used in the aircraft industry for drill jigs, as formers, stiffeners and stringers for large assembly jigs, router bases and layout tables. Used in master tooling, cast aluminum eliminates thermal problems resulting from uneven expansion. Large aluminum bars can be used to replace zinc alloys as a fixture base on spar mills with weight savings of two-thirds.

Cooking Utensils may be cast, drawn, spun, or drawn and spun. Handles are often joined to the utensil by riveting or spot welding. A cast aluminum exterior is sometimes combined with stainless steel interior.

Portable Tools use large quantities of aluminum for motor housings. Precision-cast housings are used for power drills, power saws, gasoline-driven chain saws, sanders, buffering machines, screw drivers, grinders, power shears, hammers, impact tools and for stationary bench tools.

Paper and Printing Industries. One of the principal applications is in returnable shipping cores. A tube of alloy 63S, fabricated in the same manner as irrigation tube, is used by some. The cores are reinforced with steel end-sleeves which also constitute wear-resistant drive elements. Processing or rewinding cores are fabricated of the same alloy. Fourdrinier or table rolls for paper-making machines are made of 61S.

Curved aluminum sheet printing plates permit higher rotary press speeds and minimize misregister by decreasing centrifugal force. Aluminum lithographing sheet offers good reproduction and ease of handling.

Instruments. Aluminum alloys are used in the manufacture of clocks and instruments where their light weight is an advantage. High-silicon alloys are preferred because of their castability, but anodizing must be done with care. Plates and wheels of heat treated alloys have been tested and appear to be satisfactory. Small quantities of aluminum strip are used for such items as pointers, where weight of the moving part is important.

Reflectors. Reflectivity of light is as high as 95% on specially prepared surfaces of high-purity aluminum. Aluminum is generally superior to other metals in its ability to reflect infra-red or heat rays of the sun. Heat reflectivity may be as much as 98% for a highly polished surface, reduced only slightly as the metal weathers and loses its initial brilliance. When maximum reflectivity is desired, chemical or electrochemical brightening treatments are used. A short-time anodic treatment is usually given the parts, sometimes followed by a coat of clear lacquer. Reflectors which require less brightness may simply be buffed and lacquered. When a diffuse finish is desired, it may be obtained by etching in a mild caustic solution. This finish also is protected either by clear lacquer or an anodic coating, or both.

PROPERTIES OF ALUMINUM ALLOYS

Al-1.2 Mn-1.0 Mg

A 2 Trade name. 4S

3 ASTM numbers. B178-53T, B209-53T (sheet and plate); B274-53T (drawn pipe and tube); B210-53T, B275-53T (drawn tube); B178-53T (clad sheet and plate). Alloy MG11A in all

B 1 Typical uses. Commercial roofing sheet and applications where strengths higher than 3S are required

C 1 Density at 20°C (68°F). 2.72 g per cu cm (0.098 lb per cu in.)

D 1 Liquidus temperature. 651°C (1205°F)

2 Solidus temperature. 630°C (1165°F)

6 Thermal expansion.

20 to 100°C (68 to 212°F). 0.0000232 per °C
20 to 200°C (68 to 392°F). 0.0000242 per °C
20 to 300°C (68 to 572°F). 0.0000250 per °C

16 Thermal conductivity at 25°C (77°F).

0.39 cal/sq cm/cm/°C sec, conditions O and H38

19 Recrystallization temperature. 350°C (650°F) approx., 75% reduction

E 1 Volume conductivity referred to standard copper. 42%, conditions O and H38

2 Electrical resistivity at 25°C (77°F). 4.186 microhm-cm, conditions O and H38

II Electrolytic solution potential versus N/10 calomel electrode is 0.84 volt (53 g NaCl + 3 g H₂O₂ solution), conditions O and H38

K Mechanical properties.

Condition	Tensile Strength, psi ^(a)	Yield Strength, psi ^(a)	Elongation, % ^(b)	Bhn ^(c)	Shear Strength, psi ^(d)	Endurance Limit, psi ^(e)
Annealed O ..	26,000	10,000	20	25	45	16,000
H32	31,000	22,000	10	17	52	17,000
H34	34,000	27,000	9	12	63	18,000
H36	37,000	31,000	5	9	70	20,000
H38	40,000	34,000	5	6	77	21,000

(a) Yield strength at 0.2% offset. (b) Sheet specimen $\frac{1}{2}$ in. thick.
(c) Round specimen $\frac{1}{2}$ in. diam. (d) 500-kg load, 10-mm ball. (e) Based on 500,000,000 cycles of completely reversed stress using R. R. Moore type machine and specimen

2 Directional properties (various hard tempers of sheet). Tensile strength and elongation are slightly lower in transverse direction than in longitudinal direction.

L 2 Radiography. Same as for 2S alloy.

M Composition Limits. All forms (ASTM), components: 1.0 to 1.5% Mn; 0.8 to 1.3% Mg; impurities: 0.20% max Cu; 0.7% max Fe; 0.30% max Si; 0.10% max Zn; others (total) 0.15% max

2 Consequence of exceeding impurity limits. High copper reduces resistance to corrosion; high iron plus silicon decreases formability.

N 1 Melting temperature range. 675 to 745°C (1250 to 1375°F)

3 Alloying. Add manganese as aluminum-rich alloy and magnesium as pure metal to melt-down or molten base metal.

7 Hot working temperature range. 260 to 540°C (500 to 950°F).

10 Maximum reduction between anneals. 75%

15 Heat treatment. Annealing at 343°C (650°F); holding at temperature is not required.

17 Joining. Same as 3S

Property ^(a)	Temperature, deg Fahr						
	75	212	300	400	500	600	700
Annealed O							
Tensile strength, psi	26,000	26,000	21,000	14,000	10,000	7,000	5,000
Yield strength, psi ^(b)	10,000	10,000	10,000	9,500	7,000	4,500	3,000
Elongation, % ^(c)	25	25	35	55	70	85	95
Condition H34							
Tensile strength, psi	34,000	34,000	28,000	21,000	14,000	7,500	5,000
Yield strength, psi ^(b)	27,000	27,000	24,000	15,000	7,000	4,500	3,000
Elongation, % ^(c)	12	13	22	37	96	85	95
Condition H38							
Tensile strength, psi	40,000	39,000	30,000	21,000	12,000	7,000	5,000
Yield strength, psi ^(b)	34,000	34,000	25,000	14,000	7,000	4,500	3,000
Elongation, % ^(c)	6	8	15	30	50	85	95

(a) Lowest strengths during 10,000 hr at the testing temperature.

(b) Yield strength at 0.2% offset. (c) Round specimen 1/2 in. diam

Al-1.2 Mg

A 2 Trade name. 50S

3 ASTM numbers. B178-53T, B209-53T (sheet and plate); B274-53T (extruded and drawn tubing). Alloy G1A

B 1 Typical uses. Sheet—trim in refrigerator applications; tubing—automobile gas and oil lines

C 1 Density at 20°C (68°F). 2.69 g per cu cm (0.097 lb per cu in.)

D 1 Liquidus temperature. 651°C (1205°F)

2 Solidus temperature. 627°C (1160°F)

6 Thermal expansion.

20 to 100°C (68 to 212°F). 0.0000237 per °C

20 to 200°C (68 to 392°F). 0.0000246 per °C

20 to 300°C (68 to 572°F). 0.0000255 per °C

16 Thermal conductivity at 25°C (77°F).

0.46 cal/cm²/cm/°C sec, conditions O and H38

19 Recrystallization temperature. 350°C (650°F) approx. 75% reduction

E 1 Volume conductivity referred to standard copper. 50%, conditions O and H38

Condition	Tensile Strength, psi	Yield Strength, psi ^(a)	Elongation, % ^(b)	Bhn	Shear Strength, psi	Endurance Limit, psi ^(d)
Annealed O	21,000	8,000	24	36	15,000	12,000
H32	25,000	21,000	9	46	17,000	13,000
H34	28,000	24,000	8	53	18,000	13,000
H36	30,000	26,000	7	58	19,000	14,000
H38	32,000	29,000	6	63	20,000	14,000

(a) Yield strength at 0.2% offset. (b) Sheet specimen 1/8 in. thick.
(c) 500-kg load, 10-mm ball. (d) Based on 500,000,000 cycles of completely reversed stresses using R. R. Moore type machine and specimen

2 Electrical resistivity at 25°C (77°F). 3.516 microhm-cm, conditions O and H38.

K Mechanical properties. See tables below.

2 Directional properties (various hard tempers of sheet). Tensile strength and elongation are slightly lower in transverse direction than in longitudinal direction.

M Composition Limits. All forms (ASTM), components: 1.0 to 1.8% Mg; impurities: 0.20% max Cu; 0.7% max Fe; 0.4% max Si; 0.10% max Mn; 0.25% max Zn; 0.10% max Cr; others (total) 0.15% max

2 Consequence of exceeding impurity limits. High copper reduces resistance to corrosion, high iron and silicon reduce formability, high silicon may reduce strength.

N 1 Melting temperature range. 1250 to 1375°F

7 Hot working temperature range. 500 to 950°F

10 Maximum reduction between anneals. 75%

15 Heat treatment. Annealing at 343°C (650°F); holding at temperature is not required.

17 Joining. Same as 3S

Property ^(a)	Temperature, deg Fahr						
	75	212	300	400	500	600	700
Annealed O							
Tensile strength, psi	21,000	21,000	19,000	14,000	9,000	6,000	4,000
Yield strength, psi ^(b)	8,000	8,000	8,000	8,000	5,500	4,000	3,000
Condition H34							
Tensile strength, psi	28,000	27,000	24,000	14,000	9,000	6,000	4,000
Yield strength, psi ^(b)	24,000	24,000	21,000	8,000	5,500	4,000	3,000
Condition H38							
Tensile strength, psi	32,000	31,000	26,000	14,000	9,000	6,000	4,000
Yield strength, psi ^(b)	29,000	29,000	24,000	8,000	5,500	4,000	3,000

(a) Lowest strengths in 10,000 hr. (b) Yield strength at 0.2% offset

Al-0.7 Mg-0.4 Si

A 2 Trade name. 63S

3 ASTM numbers. B241-53T, B274-53T (extruded or drawn pipe); B221-53T (extruded shapes); B235-53T (extruded tube). Alloy GS10A in all

B 1 Typical uses. Extrusions—architectural applications; tubing—irrigation pipe

C 1 Density at 20°C (68°F). 2.70 g per cu cm (0.098 lb per cu in.)

D 1 Liquidus temperature. 651°C (1205°F)

2 Solidus temperature. 616°C (1140°F)

6 Thermal expansion.

20 to 100°C (68 to 212°F). 0.0000234 per °C

20 to 200°C (68 to 392°F). 0.0000245 per °C

20 to 300°C (68 to 572°F). 0.0000255 per °C

16 Thermal conductivity at 25°C (77°F).

0.48 cal/cm²/cm/°C sec, condition T6

0.51 cal/cm²/cm/°C sec, condition T83

19 Recrystallization temperature. 350°C (650°F) approx. 75% reduction

E 1 Volume conductivity referred to standard copper. 53%, condition T6; 56%, condition T83.

Condition	Tensile Strength, psi	Yield Strength, psi ^(a)	Elongation, % ^(b)	Bhn	Shear Strength, psi	Endurance Limit, psi ^(d)
T6	27,000	21,000	12	60	17,000	9,500
T83	35,000	31,000	12	73	22,000	9,500
T83	37,000	35,000	11	82	22,000	.....

(a) Yield strength at 0.2% offset. (b) Sheet specimen 1/8 in. thick.
(c) 500-kg load, 10-mm ball. (d) Based on 500,000,000 cycles of completely reversed stresses using R. R. Moore type machine and specimen

2 Electrical resistivity at 25°C (77°F). 3.317 microhm-cm, condition T6; 3.140 microhm-cm, condition T83

11 Electrolytic solution potential versus 0.1N calomel electrode is 0.84 volt (53 g NaCl + 3 g H₂O₂ solution), conditions T5 and T6

K Mechanical properties. See tables below.

M Composition Limits. All forms (ASTM), components: 0.45 to 0.9% Mg; 0.2 to 0.6% Si; impurities: 0.10% max Cu; 0.35% max Fe; 0.10% max Zn; 0.10% max Cr; 0.10% max Mn; 0.10% max Ti; others (total) 0.15% max

2 Consequences of exceeding impurity limits. High iron reduces formability, may reduce corrosion resistance.

N 1 Melting temperature range. 1250 to 1350°F

3 Alloying. Add magnesium and silicon as pure metals or aluminum-rich alloy to molten base metal.

7 Hot working temperature range. 500 to 950°F

15 Heat treatment. Precipitation T5 232°C (450°F), 1 to 2 hr, cooling not critical; precipitation T6 177°C (350°F), 6 to 8 hr, cooling not critical

17 Joining. Same as 61S

Property ^(a)	Temperature, deg Fahr						
	75	212	300	400	500	600	700
Condition T5							
Tensile strength, psi	27,000	24,000	20,000	9,000	4,500	3,000	2,500
Yield strength, psi ^(b)	21,000	20,000	18,000	6,500	3,500	2,500	2,000
Elongation, % ^(c)	22	18	20	40	75	80	105
Condition T6							
Tensile strength, psi	35,000	31,000	21,000	9,000	4,500	3,000	2,500
Yield strength, psi ^(b)	31,000	28,000	20,000	6,500	3,500	2,500	2,000
Elongation, % ^(c)	18	15	20	40	75	80	105

(a) Lowest strengths during 10,000 hr at the testing temperature.

(b) Yield strength at 0.2% offset. (c) Round specimen 1/2 in. diam

Al-9 Si-3.5 Cu-0.8 Mg-0.8 Ni

- A 2 Trade name.** D132 alloy (permanent-mold casting)
- B 1 Typical uses.** Applications where good high-temperature strength, low coefficient of thermal expansion, and good resistance to wear are required. Automotive and Diesel pistons, pulleys, and sheaves are typical.
- C 1 Density at 20°C (68°F).** 2.76 g per cu cm (0.100 lb per cu in.)
- D 1 Liquidus temperature.** 582°C (1080°F)
- 2 Solidus temperature.** 520°C (970°F)
- 6 Thermal expansion.**
- 20 to 100°C (68 to 212°F). 0.0000205 per °C
 - 20 to 300°C (68 to 572°F). 0.0000223 per °C
- 11 Specific heat at 100°C (212°F).** Approx 0.23 cal per g
- 13 Latent heat of fusion.** Approx 93 cal per g
- 16 Thermal conductivity at 25°C (77°F).** 0.25 cal/sq cm/°C/sec, condition T5
- E 1 Volume conductivity referred to standard copper.** 26%, condition T5
- 2 Electrical resistivity at 20°C (68°F).** 6.631 microhm-cm, condition T5
- 11 Electrolytic solution potential versus N/10 calomel electrode is -0.78 volt, condition T5 (53 g NaCl + 3 g H₂O₂ solution)**
- F 5 Emissivity.** 0.035 to 0.07 at 25°C (77°F) in air
- K Mechanical properties. Permanent-mold cast, condition T5:** Tensile strength 36,000 psi; yield strength 28,000

psi; compressive yield strength 28,000 psi; elongation (round specimens, ½-in. diam) 1.0%; Bhn (500-kg load, 10-mm ball) 105; modulus of elasticity 10,300,000 psi; shear strength 28,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

Property ^(a)	Temperature, deg Fahr					
	75	212	300	400	500	600
Tensile strength, psi	36,000	33,000	28,000	20,000	14,000	9,000
Yield strength, psi	28,000	26,000	23,000	13,000	9,000	6,000
Elongation, %	1.0	1.5	2.0	5.0	10.0	20.0
(a)	Lowest strengths during 10,000 hr at testing temperature					

- L 2 Radiography.** Same as for A132 alloy
- M Composition Limits. Permanent-mold cast, Components:** 2.0 to 4.0% Cu; 8.5 to 10.5% Si; 0.5 to 1.5% Mg; 0.5 to 1.5% Ni; **impurities (max):** 1.2% Fe; 0.5% Mn; 0.5% Zn; 0.2% Ti; others (total) 0.5%
- 2 Consequences of exceeding impurity limits.** High iron promotes shrinkage difficulties.
- N 1 Melting temperature.** 677 to 816°C (1250 to 1500°F)
- 2 Casting temperature.** 677 to 788°C (1250 to 1450°F)
- 3 Alloying.** Same as for A132 alloy
- 5 Type of flux for remelting for casting.** Same as 138
- 15 Heat treatment.** No solution heat treatment. Condition T5, 7 to 9 hr at 204°C (400°F), cooling not critical.

Al-10.0 Cu-4.0 Si-0.3 Mg

- A 2 Trade name.** 138 alloy (permanent-mold casting)
- B 1 Typical uses.** Applications where a combination of high hardness in as-cast condition, good casting characteristics and good machinability are required. Sole plates for electric hand irons are typical.
- C 1 Density at 20°C (68°F).** 2.95 g per cu cm (0.107 lb per cu in.)
- D 1 Liquidus temperature.** 544°C (1110°F)
- 2 Solidus temperature.** 496°C (925°F)
- 6 Thermal expansion.**
- 20 to 100°C (68 to 212°F). 0.0000214 per °C
 - 20 to 200°C (68 to 392°F). 0.0000225 per °C
 - 20 to 300°C (68 to 572°F). 0.0000228 per °C
- 11 Specific heat at 100°C (212°F).** Approx 0.23 cal per g
- 13 Latent heat of fusion.** Approx 93 cal per g
- 16 Thermal conductivity at 25°C (77°F).** 0.24 cal/sq cm/°C/sec.
- E 1 Volume conductivity referred to standard copper.** 25%.
- 2 Electrical resistivity at 20°C (68°F).** 6.894 microhm-cm
- 11 Electrolytic solution potential versus N/10 calomel elec-**

- trode is -0.74 volt (53 g NaCl + 3 g H₂O₂ solution)
- F 5 Emissivity.** 0.035 to 0.07 at 25°C (77°F) in air
- K Mechanical Properties. Permanent-mold cast:** Tensile strength 30,000 psi; yield strength 24,000 psi; compressive yield strength 30,000 psi; elongation (round specimens, ½-in. diam) 1.5%; Bhn (500-kg load, 10-mm ball) 100; modulus of elasticity 10,300,000 psi; shear strength 24,000 psi; modulus of rigidity 3,850,000 psi
- L 2 Radiography.** Same as for 122 alloy (Al-10 Cu-0.2 Mg)
- M Composition Limits. Permanent Mold Cast, Components:** 9.5 to 10.5% Cu; 3.5 to 4.5% Si; 0.15 to 0.35% Mg; **impurities (max):** 1.5% Fe; 0.5% Mn; 0.5% Zn; 0.5% Ni; 0.2% Ti; others (total) 0.5%
- N 1 Melting temperature.** 677 to 816°C (1250 to 1500°F)
- 2 Casting temperature.** 677 to 788°C (1250 to 1450°F)
- 3 Alloying.** Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal.
- 5 Type of flux for remelting for casting.** Gaseous type nitrogen or chlorine; or solid type, chloride base

Al-3.8 Mg-1.8 Si

- A 2 Trade name.** B214 alloy (sand and permanent-mold)
- 3 ASTM number.** B26-52T, Alloy GS42A (sand); B108-52T, Alloy GS42A (permanent mold)
- B 1 Typical uses.** Applications where excellent resistance to corrosion and tarnishing are required. Cooking utensils and pipe fittings for marine as well as for general use.
- C 1 Density at 20°C (68°F).** 2.65 g per cu cm (0.096 lb per cu in.)
- D 1 Liquidus temperature.** 632°C (1170°F)
- 2 Solidus temperature.** 587°C (1090°F)
- 6 Thermal expansion.**
- 20 to 100°C (68 to 212°F). 0.0000228 per °C
 - 20 to 200°C (68 to 392°F). 0.0000239 per °C
 - 20 to 300°C (68 to 572°F). 0.0000248 per °C
- 11 Specific heat at 100°C (212°F).** Approx 0.23 cal per g
- 13 Latent heat of fusion.** Approx 93 cal per g
- 16 Thermal conductivity at 25°C (77°F).** 0.35 cal/sq cm/°C/sec.
- E 1 Volume conductivity referred to standard copper.** 38%
- 2 Electrical resistivity at 20°C (68°F).** 4.537 microhm-cm
- 11 Electrolytic solution potential versus N/10 calomel electrode is -0.86 volt (53 g NaCl + 3 g H₂O₂ solution)**
- F 5 Emissivity.** 0.035 to 0.07 at 25°C (77°F) in air
- K Mechanical Properties. Sand cast:** Tensile strength 20,000 psi; yield strength 13,000 psi; compressive yield strength 14,000 psi; elongation (round specimens ½-in.

- diam) 2.0%; Bhn (500-kg load, 10-mm ball) 50; modulus of elasticity 10,300,000 psi; shear strength 17,000 psi; modulus of rigidity 3,850,000 psi
- L 2 Radiography.** Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-140 unit, 2.0 H & D film density
- | Section, in. | Volts | Milliamp | Time, min |
|--------------|---------|----------|-----------|
| 1½ | 60,000 | 8.0 | 1.0 |
| 1 | 90,000 | 7.0 | 1.0 |
| 1½ | 110,000 | 6.0 | 1.0 |
| 2 | 135,000 | 5.0 | 1.0 |
- M Composition Limits. Sand Cast, Components:** 3.5 to 4.5% Mg; 1.4 to 2.2% Si; **impurities (max):** 0.3% Cu; 0.6% Fe; 0.8% Mn; 0.3% Zn; 0.2% Ti; 0.2% Cr; others (each) 0.05%
- 2 Consequences of exceeding impurity limits.** High copper, nickel, or tin impairs resistance to corrosion. High iron decreases strength and ductility.
- N 1 Melting temperature.** 677 to 816°C (1250 to 1500°F)
- 2 Casting temperature.** 677 to 788°C (1250 to 1450°F)
- 3 Alloying.** Add magnesium as pure metal to molten base metal (pure). Add silicon as pure metal or aluminum-rich alloy to base metal (pure).
- 5 Type of flux for remelting for casting.** Same as 138
- 17 Joining. Rivet compositions.** 53S-T4, 53S-T6, 53S-T61. **Other joining methods.** Same as for 214 alloy

Typical Properties of Aluminum Alloys

(Alloys not included in 1948 Metals Handbook or on pages 60 to 62 in this Supplement)

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation, %	Brinell Hardness ^(a)	Shear Strength, psi	Fatigue Limit, ^(b) psi	Composition Limits
Al - 2.5 Cu - 0.3 Mg (A17S) Rivet Wire and Rivets (AMS 7222)							
T4	43,000	24,000	27	70	28,000	13,500	AMS 7222. Components, 2.2 to 3.0% Cu; 0.20 to 0.50% Mg; impurities (max), 1.00% Fe; 0.80% Si; 0.20% Mn; 0.10% Zn; 0.25% Cr; others (each) 0.05% (total) 0.15%
Al - 4.0 Cu - 2.0 Ni - 1.5 Mg (B18S) Forging Stock (ASTM CN42D)							
T61	55,000	40,000	—	—	—	—	ASTM CN42D (B247-50T). Components, 3.5 to 4.5% Cu; 1.7 to 2.3% Ni; 1.2 to 1.8% Mg; impurities (max), 1.0% Fe; 0.90% Si; 0.20% Mn; 0.25% Zn; 0.10% Cr; others (each) 0.05% (total) 0.15%
T71	50,000	40,000	—	—	—	—	
T72	48,000	37,000	11	95	30,000	—	
Al - 2.0 Cu - 1.0 Fe - 1.5 Mg - 1.0 Ni (F18S) Forging Stock							
T61	64,000	54,000	10	125	38,000	20,000	(Limits not established)
Al - 0.8 Mg (A50S, K155 and R305) Plate and Sheet							
O	17,000	6,000	31 ^(c)	28	11,000	—	Commercial A50S, K155 and R305. Components, 0.50 to 1.1% Mg; impurities (max), 0.20% Cu; 0.7% Fe; 0.40% Si; 0.20% Mn; 0.25% Zn; 0.10% Cr; others (each) 0.05% (total) 0.15%
H12	20,000	19,000	10 ^(c)	—	—	—	
H14	23,000	22,000	5 ^(c)	—	—	—	
H16	26,000	25,000	4 ^(c)	—	—	—	
H18	29,000	26,000	3 ^(c)	—	—	—	
H32	20,000	17,000	10 ^(c)	36	12,000	—	
H34	23,000	20,000	8 ^(c)	41	13,000	—	
H36	26,000	24,000	5 ^(c)	46	15,000	—	
H38	28,000	25,000	6 ^(c)	51	17,000	—	
Al - 0.6 Mg - 0.35 Si - 0.25 Cu (J51S) Sheet							
O	17,000	6,000	28	—	—	—	Commercial J51S. Components, 0.40 to 0.8% Mg; 0.20 to 0.50% Si; 0.15 to 0.40% Cu; impurities (max), 0.8% Fe; 0.20% Zn; others (each) 0.05% (total) 0.15%
T3	20,000	13,000	—	—	—	—	
T4 ^(d)	25,000	11,000	—	—	—	—	
T4 ^(e)	20,000	6,500	—	—	—	—	
T6 ^(f)	35,000	30,000	10	—	—	—	
T6 ^(g)	29,000	18,000	—	—	—	—	
Al - 3.5 Mg - 0.25 Cr							
(A54S) Plate, Sheet, Rod, Bar, Shapes, Pipe and Tube (ASTM GR40A)							
O	34,000	15,000	27 ^(c)	58	21,000	17,000	ASTM GR40A (B178-53T—plate and sheet): B273-53T bars, rods and shapes; B274-53T pipe and tube. Components, 3.1 to 3.9% Mg; 0.15 to 0.35% Cr; impurities (max), 0.10% Cu; 0.45% Fe plus Si; 0.10% Mn; 0.20% Zn; Ti; others (each) 0.05% (total) 0.15%
H32	39,000	29,000	15 ^(c)	67	22,000	18,000	
H34	42,000	33,000	13 ^(c)	73	24,000	19,000	
H36	45,000	36,000	12 ^(c)	78	26,000	20,000	
H38	47,000	39,000	10 ^(c)	87	27,000	21,000	
H112	35,000	16,000	25 ^(c)	—	—	17,000	
Al - 4.5 Mg - 0.5 Mn Clad With Al - 1.0 Zn							
(Clad 55S) Plate and Sheet							
O	38,000	20,000	—	—	—	—	Commercial Alclad 55S. Core; components, 4.0 to 5.0% Mg; 0.30 to 0.80% Mn; impurities (max), 0.25% Cu; 0.70% Fe plus Si; 0.30% Si; 0.25% Zn; 0.25% Cr; others (each) 0.05% (total) 0.15%. Cladding; components, 0.75 to 1.25% Zn; impurities (max), 0.10% Cu; 0.60% Fe plus Si; 0.10% Mn; others (each) 0.05% (total) 0.15%
H34	48,000	36,000	—	—	—	—	
H36	52,000	40,000	—	—	—	—	
H111	39,000	24,000	—	—	—	—	
Al - 1.0 Mg - 0.3 Mn (C57S) Plate and Sheet							
O	19,000	7,000	25 ^(c)	32	12,000	—	Commercial C57S. Components, 0.8 to 1.2% Mg; 0.15 to 0.45% Mn; impurities (max), 0.07% Cu; 0.17% Fe; 0.12% Si; others (each) 0.05% (total) 0.15%
H32	22,000	19,000	9 ^(c)	40	13,000	—	
H34	25,000	22,000	8 ^(c)	45	15,000	—	
H36	28,000	26,000	7 ^(c)	51	17,000	—	
H38	32,000	30,000	6 ^(c)	55	18,000	—	
Al - 1.0 Mg - 0.6 Si - 0.25 Cu - 0.25 Cr Clad With Al - 1.0 Zn							
(Clad 61S) Plate and Sheet for Pressure Vessels (ASTM GS11)							
O	17,000	7,000	25 ^(c)	—	11,000	—	ASTM GS11A (B178-52T). Core; components, 0.80 to 1.2% Mg; 0.40 to 0.80% Si; 0.15 to 0.40% Cu; 0.15 to 0.35% Cr; impurities (max), 0.25% Fe; 0.15% Mn; 0.20% Zn; 0.15% Ti; others (each) 0.05% (total) 0.15%. Cladding; components, 0.75 to 1.25% Zn; impurities (max), 0.10% Cu; 0.60% Fe plus Si; 0.10% Mn; others (each) 0.05% (total) 0.15%
T4	33,000	19,000	22 ^(c)	—	22,000	—	
T6	42,000	37,000	12 ^(c)	—	27,000	—	
Al - 1.0 Mg - 0.6 Si - 0.25 Cu - 0.1 Cr							
(62S) Extruded Rod, Bar and Shapes							
O	15,000	7,000	30	28	12,000	9,000	Commercial 62S. Components, 0.8 to 1.2% Mg; 0.40 to 0.80% Si; 0.15 to 0.40% Cu; 0.04 to 0.15% Cr; impurities (max), 0.20% Fe; 0.15% Mn; 0.20% Zn; 0.15% Ti; others (each) 0.05% (total) 0.15%
T4	35,000	21,000	25	65	24,000	14,000	
T6	45,000	40,000	17	95	30,000	14,000	
Al - 4.0 Mg - 0.5 Si (F214) Sand Castings							
F	21,000	12,000	3	50	17,000	—	Commercial F214. Components, 3.5 to 4.5% Mg; 0.3 to 0.7% Si; impurities (max), 0.1% Cu; 0.4% Fe; 0.3% Mn; 0.1% Zn; 0.2% Ti; others (each) 0.05%
Al - 6.5 Zn - 0.7 Mg - 0.5 Cu (A612) Sand Castings (ASTM ZG61B)							
T5	35,000	25,000	5	75	26,000	8,000	ASTM ZG61B (B26-52T). Components, 6.0 to 7.0% Zn; 0.60 to 0.80% Mg; 0.35 to 0.65% Cu; impurities (max), 0.5% Fe; 0.15% Si; 0.05% Mn; 0.20% Ti; others (each) 0.05% (total) 0.15%
Al - 3.0 Zn - 1.6 Mg - 0.5 Mn - 0.3 Cr (Ternalloy 5) Sand Castings (ASTM ZG32A)							
F	29,000	13,000	12	50	—	—	ASTM ZG32A (B26-52T and B108-52T). Components, 2.7 to 3.3% Zn; 1.4 to 1.8% Mg; 0.4 to 0.6% Mn; 0.2 to 0.4% Cr; impurities (max), 0.2% Cu; 0.8% Fe; 0.2% Si; 0.2% Ti; 0.2% Ni; others 0.5% each
(f)	35,000	19,000	9	65	—	—	
Chill Castings							
F	33,000	15,000	22	55	—	—	ASTM ZG42A (B26-52T and B108-52T). Components, 4.0 to 4.5% Zn; 1.8 to 2.4% Mg; 0.4 to 0.6% Mn; 0.2 to 0.4% Cr; impurities (max), 0.2% Cu; 0.8% Fe; 0.2% Si; 0.2% Ti; 0.2% Ni; others 0.5% each
(f)	42,000	21,000	18	70	—	—	
Al - 4.25 Zn - 2.1 Mg - 0.5 Mn - 0.3 Cr (Ternalloy 7) Sand Castings (ASTM ZG42A)							
F	30,000	19,000	5	65	—	—	thick. (d) Cooling during treatment by water quenching.
(f)	37,000	27,000	3	85	—	—	(e) Cooling during treatment by air cooling.
T6 ^(g)	44,000	40,000	1.5	80	—	—	(f) 21 days at room temperature or 8 hr at 210 F.
T7 ^(h)	43,000	33,000	1.5	80	—	—	(g) 4 to 16 hr at 980 to 1000 F, cold water quench, 3 to 5 hr at 290 to 310 F.
F	42,000	24,000	14	75	—	—	(h) 4 to 16 hr at 980 to 1000 F, cold water quench, 4 to 6 hr at 340 to 360 F.
(f)	47,000	29,000	8	85	—	—	
T6 ^(g)	49,000	36,000	9.5	95	—	—	
T7 ^(h)	53,000	43,000	6.5	95	—	—	
(a) 500-kg load; 10-mm ball. (b) Based on 500,000,000 cycles using R. R. Moore-type rotating beam machine. (c) Sheet specimen $\frac{1}{8}$ in.							

Selection of Copper and Copper Alloys

By the ASM Committee on Copper

THIS article is intended to assist in the selection of copper alloys; it is therefore divided according to the principal factors which govern particular uses. Thus, electrical and thermal conductivity, strength, formability, machinability, surface finish, joining ability and corrosion resistance are principal subdivisions for the wrought materials; for casting alloys, castability, mechanical properties, bearing and wear qualities, corrosion resistance and electrical-thermal conductivity are considered.

Because of the many interconnections among the principal factors, reference is made under each principal heading to a number of the other factors which are closely related for the applications discussed.

WROUGHT FORMS

Nominal compositions of the wrought alloys are listed in Table I.

Electrical Conductivity. Electrolytic tough pitch copper is the preferred material for current-carrying members. Conductivity is 100% (Table II) in the softest temper with 32,000 psi tensile strength, and 97% in spring rolled temper at 50,000 to 55,000 psi tensile strength.

Temperature above 400 F will soften tough pitch copper to a tensile strength of 30,000 to 35,000 psi. The three silver-bearing coppers resist softening up to about 650 F, and are less susceptible to stress-rupture in highly stressed parts such as turbo-generator windings, and high-speed commutators. If electrolytic copper is exposed to temperatures above 700 F and reducing gases, especially hydrogen, embrittlement may take place. Oxygen-free copper or phosphor-deoxidized copper is then specified.

A combination of 70,000 psi tensile strength with conductivity of 80% and higher, suited to spot welding tips and seam welding wheels, can be obtained with heat treated chromium copper, which is available in some forms.

Where tensile strength up to 215,000 psi and fatigue strength of 36,000 psi are required and where the penalty of 17% conductivity and high cost are tolerable, heat treated beryllium copper can be used if the combined effect of ambient temperature and electrical resistance of the part holds temperatures below 700 F.

Conducting springs, contacts and similarly highly stressed members which also may have to be formed may use chromium copper or beryllium copper. Parts are shaped soft and then strengthened by heat treatment.

Parts which must be highly machined and highly conductive should be made from the free-machining coppers. The most used is tellurium copper.

Supplements the Copper Section of the 1948 ASM Metals Handbook, pages 841 to 942

WROUGHT FORMS

	Page
Electrical Conductivity	64
Thermal Conductivity	64
Mechanical Strength	64
Formability	65
Machinability	66
Surface Finish	66
Joining	66
Corrosion Resistance	67

CASTINGS

Castability	68
Machinability	68
General-Purpose Alloys	68
Mechanical Properties	69
Bearing and Wear Properties	71
Corrosion	72
Electrical and Thermal Conductivity	72

per which has 90% conductivity and 90% machinability. Leaded copper (1% Pb) or selenium copper (0.6% Se) is also used because of the 80% machinability ratings with most other properties similar to copper. If tensile strengths of 64,000 to 76,000 psi are required at 80% machinability, heat treated and hard drawn forms of tellurium-nickel copper should be chosen, provided electrical conductivity of 50% is permissible.

Thermal Conductivity

The thermal conductivity changes induced by the alloying of copper are of the same magnitude as those for electrical conductivity (Table II). Major heat-exchange applications are in automotive heaters and radiators, heating coils of all types, air conditioning condensers and evaporators, soldering irons, welding torch tips and resistance welding electrodes. While surface area and film coefficients frequently affect total heat flow more than metal conductivity itself, equipment requiring heat exchange of high order may best use copper.

Heating coils are made of tubing which, if bent, is specified in deoxidized copper at soft temper or with light cold working to increase temper for better handling. The same applies to air conditioning and refrigeration coils for evaporators and condensers. Welding torch tips may be swaged to shape from rod, preferably of soft temper. In machined soldering iron and welding torch tips, free-cutting copper is superior.

Soft solder is widely used in the manufacture of radiators and heaters, as well as for similar applications where the operating temperatures are within the limitations of soft solder.

Welding torch tips and soldering irons are not subject to corrosion as such. Refrigeration and air conditioning equipment may be in contact with water or air, or both, and also may be

exposed to various "Freons", ammonia, sulfur dioxide and bromide-water solutions. All Freons are noncorrosive to copper and its alloys. Copper can be used where ammonia or sulfur dioxide is involved only if these are anhydrous. Bromide-water solutions are best handled by cupro-nickel, with copper a second choice.

Corrosion is not serious in most U. S. fresh waters admitted to heat-exchange equipment. Salt or brackish waters call for cupro-nickel, inhibited aluminum brass or inhibited admiralty metal, in descending order of excellence and allowable water velocity.

Atmospheric corrosion is not a serious problem except in seacoast areas, or in highly contaminated industrial sections. Electrolytic action may be severe under these conditions, if the potential difference between dissimilar metals is high (see page 895 of the 1948 Metals Handbook).

Mechanical Strength

Strength is determined principally by composition and cold work, except for the heat treatable alloys. Applications may be divided into three categories listed in Table III.

Copper and copper-zinc alloys with aluminum, tin, silicon, iron and manganese in various combinations are much stronger than other coppers or brasses. For heavy sections of plate, rod and bar, inherently strong alloys such as aluminum bronze or silicon bronze should be specified. For light sections which can be obtained in the stronger tempers, other alloys may be adequate.

Yield Strength of copper alloys is usually taken arbitrarily at 0.5% extension under load, although this may not be the value most pertinent in design. Values for 0.1 or 0.2% offset yield may be more useful.

Where residual stresses are high enough to cause stress-corrosion cracking or where stresses from forming may give rise to drift in springs, diaphragms and other stressed members, low-temperature stress relieving is advisable.

In spring applications choice of temper is limited by severity of the forming operations. For pressure vessels, roll forming of sides and hot or cold forming of heads are involved. Alloys in Table III are adaptable to such shaping, and the choice usually depends on weldability or corrosion resistance. Naval brass, however, cannot be cold formed readily.

All cold worked alloys will be softened by temperatures incident to the brazing and welding of pressure vessel components. Spot and seam welding may be controlled so that little softening occurs and high enough strength is retained for most purposes.

Machinability of aluminum-silicon bronze rod is good enough to make this alloy suitable for high-strength applications. Tellurium-nickel copper also meets the requirements, but is a more expensive alloy and must be heat treated. Leaded naval brass and free-cutting brass rod are less costly but lower in strength.

Fatigue Strength is an important consideration in the design of springs, diaphragms, bellows, flexible hose and similar applications. The best alloys, in approximately descending order, are: beryllium copper, phosphor bronze D, C and A; nickel silver B and silicon

bronze A. The first note in Table III gives some approximate values.

Temperatures as low as -300°F do not embrittle copper alloys and do impart a slight gain in strength and toughness. In high-temperature uses, 70-30 cupro-nickel and 10% aluminum bronze are advantageous because of their oxidation resistance. Most copper alloys soften between 400 and 800°F, depending on the amount of cold work during fabrication and the alloy involved. Creep rates and oxidation resistance are low by alloy steel standards. The Unfired Pressure Vessel Code of the ASME is one of the best references for stress and temperature limitations.

Formability

Best results in cold forming operations are obtained with the nonleaded alloys, including electrolytic tough pitch, silver-bearing, deoxidized and oxygen-free coppers; all nonleaded brasses over 63% Cu; all phosphor bronzes; silicon bronzes A and B; nickel silver A; cupro-nickels; and the heat treatable alloys in the solution annealed condition.

All coppers form readily and work harden slowly. Occasionally oxygen-free and deoxidized copper may be best for severe cold forming. Deoxidized copper is almost always used for tubular products.

Cartridge brass (70% Cu) is most popular for operations such as cold drawing, upsetting and bending, whether in strip, rod or tube form. Red brass (85% Cu), commercial bronze (90% Cu) and gilding metal (95% Cu) are not so strong, but harden slowly, permitting successive operations without intermediate annealing.

Deep drawing, coining, flanging or similar cold working all require annealed material, usually specified by grain size. Thus, light gages of strip may have grain size less than 0.050 mm. and heavy gages more than this figure. Coining operations require metal of large grain size for maximum sharpness of impression. Cold upsetting, especially of screws, rivets and bolts, should be done on metal lightly cold drawn to develop some strength in unsupported sections to resist bending. Silicon bronze B is an exception be-

cause it can be cold upset in "bolt temper" (see ASTM B98).

Forging brass, architectural bronze and aluminum-silicon bronze are not adapted to most cold working operations. Annealed tellurium and selenium copper may be cold worked extensively and are so used, especially for welding torch tips.

Bending properties of cold rolled strip vary with thickness, rolling direction and temper. Most of the non-leaded alloys can be bent 90° in any direction at 0.020 gage in 2 numbers hard. Oxygen-free copper will bend sharply at 4 numbers hard. Between 4 and 6 numbers hard, radii of 1/16 to 3/32 in. are minimum for bends parallel to the rolling direction; if bends are perpendicular, radii may need to be increased to 1/4 in. In spring temper (8 numbers hard) radii of 3/32 to 1/2 in. are needed.

Leaded brass strip is used for keys, watches and clocks but free-cutting alloys do not bend well and should be avoided unless machining also is required.

Parts blanked from strip and subsequently punched, pierced or shaved are best made from a leaded brass like alloy 5 in ASTM B121 (65% Cu, 2% Pb), rather than nonleaded material. For cold drawing into limited shapes, along with good machinability, alloy 3 in this specification (1% Pb) is a better choice.

Hot Forming is best suited to the two-phase alloys, although infrequently single-phase alloys may be used (ASTM B124). Die-pressed forgings and extrusions are most often made from leaded brass. In the hot forming of leaded alloys, the metal should be completely supported to avoid cracking.

Alloys commonly specified for hot

Table I. Nominal Compositions of Wrought Copper Alloys^(a)

Alloy	Composition, %	Alloy	Composition, %
Coppers			
Electrolytic tough pitch (ETP)	.99.90 Cu - 0.04 O		
Phosphorized, high residual phosphorus (DHP)	.99.90 Cu - 0.02 P		
Phosphorized, low residual phosphorus (DLP)	.99.90 Cu - 0.005 P		
Lake	.Cu - 8 oz./ton Ag		
Silver-bearing (10-15)	.Cu - 10 to 15 oz./ton Ag		
Silver-bearing (25-30)	.Cu - 25 to 30 oz./ton Ag		
Oxygen-free (OF) (no residual deoxidants)	.99.92 Cu (min)		
Free-cutting	.99 Cu - 1 Pb		
Free-cutting	.99.5 Cu - 0.5 Te		
Free-cutting	.99.4 Cu - 0.6 Se		
Chromium copper (heat treatable)	.Cu + Cr and Ag or Zn		
Cadmium copper	.99 Cu - 1 Cd		
Tellurium-nickel copper (heat treatable)	.98.4 Cu - 1.1 Ni - 0.5 Te		
Beryllium copper (heat treatable)	.Cu - 2 Be - 0.25 Co or 0.35 Ni		
Plain Brasses			
Gilding metal	.95 Cu - 5 Zn		
Commercial bronze	.90 Cu - 10 Zn		
Red brass	.85 Cu - 15 Zn		
Low brass	.80 Cu - 20 Zn		
Cartridge brass	.70 Cu - 30 Zn		
Drawing brass	.65 Cu - 35 Zn		
Muntz metal	.60 Cu - 40 Zn		
Free-Cutting Brasses			
Leaded commercial bronze (rod)	.89 Cu - 9.25 Zn - 1.75 Pb		
Leaded brass strip (B121-3)	.65 Cu - 34 Zn - 1 Pb		
Leaded brass strip (B121-5)	.65 Cu - 33 Zn - 2 Pb		
Leaded brass tube (B135-3)	.66 Cu - 33.5 Zn - 0.5 Pb		
Leaded brass tube (B135-4)	.66 Cu - 32.4 Zn - 1.6 Pb		
Medium-leaded brass rod	.64.5 Cu - 34.5 Zn - 1 Pb		
High-leaded brass rod	.62.5 Cu - 35.75 Zn - 1.75 Pb		
Free-cutting brass rod (B16)	.61.5 Cu - 35.5 Zn - 3 Pb		
Forging brass	.60 Cu - 38 Zn - 2 Pb		
Architectural bronze	.57 Cu - 40 Zn - 3 Pb		
Miscellaneous Brasses			
Admiralty metal (inhibited)		.71 Cu - 28 Zn - 1 Sn	
Naval brass		.60 Cu - 39.25 Zn - 0.75 Sn	
Leaded naval brass		.60 Cu - 37.5 Zn - 1.75 Pb - 0.75 Sn	
Aluminum brass (inhibited)		.76 Cu - 22 Zn - 2 Al	
Manganese brass		.70 Cu - 28.7 Zn - 1.3 Mn	
Manganese bronze rod A (B138)		.58.5 Cu - 39 Zn - 1.4 Fe - 1 Sn - 0.1 Mn	
Manganese bronze rod B (B138)		.65.5 Cu - 23.3 Zn - 4.5 Al - 3.7 Mn - 3 Fe	
Phosphor Bronzes			
Grade A		.95 Cu - 5 Sn	
Grade B (rod, B139, Alloy B1)		.94 Cu - 5 Sn - 1 Pb	
Grade C		.92 Cu - 8 Sn	
Grade D		.90 Cu - 10 Sn	
Grade E		.98.75 Cu - 1.25 Sn	
444 bronze rod (B139, Alloy B2)		.88 Cu - 4 Zn - 4 Sn - 4 Pb	
Miscellaneous Bronzes			
Silicon bronze A ^(b)		.Cu - 3 Si - 1 Mn	
Silicon bronze B ^(b)		.Cu - 1.75 Si - 0.3 Mn	
Aluminum bronze 5%		.95 Cu - 5 Al	
Aluminum bronze 7%		.91 Cu - 7 Al - 2 Fe	
Aluminum bronze 10% ^(c)		.Cu - 9.5 Al	
Aluminum-silicon bronze		.91 Cu - 7 Al - 2 Si	
Nickel Alloys			
Cupro-nickel 10%		.88.5 Cu - 10 Ni - 1.5 Fe	
Cupro-nickel 30%		.69.5 Cu - 30 Ni - 0.5 Fe	
Nickel silver A		.65 Cu - 17 Zn - 18 Ni	
Nickel silver B		.55 Cu - 27 Zn - 18 Ni	
Leaded nickel silver rod (B151)		.62 Cu - 19 Zn - 18 Ni - 1 Pb	

(a) For another recent tabulation of compositions and properties, together with machining and fabricating characteristics, refer to data sheet, "Standard Commercial Wrought Copper and Brasses, Nonleaded and Leaded", Metal Progress, December 1952.

(b) One or more of the elements tin, manganese, iron and zinc, or a combination of iron and nickel may be present also. (c) Iron, nickel and manganese may be present in amounts totaling up to 11% in 10% aluminum bronze.

forming include many coppers, brasses with less than 63% Cu, naval brass, manganese bronze, leaded brasses, aluminum-silicon bronze (7% Al, 2% Si), silicon bronze A and cupro-nickel.

Important data pertaining to forming methods and characteristics will be found on pages 859 and 867 of the 1948 Metals Handbook.

Machinability

Most copper alloy parts made on high-speed automatic screw machines are specified to be of free-cutting brass rod in $\frac{1}{2}$ -hard temper. The applications include components for automobiles, refrigeration and air conditioning equipment, decorative elements, plumbing, hardware, camera parts, valves, screws and hundreds of others. Free-cutting copper is popular for welding torch tips, soldering iron points and miscellaneous electrical units. Relative machinability of principal copper-base alloys is listed in Table IV.

Lead does not dissolve in copper alloys but is finely dispersed throughout the alloy matrix. As a result it provides a lubricant for the cutting tool and results in relatively low tool wear. It breaks the chips so they are easily flushed away by lubricants. Finishes are very good with proper tools and feeds, and machining rates are frequently as high as maximum machine capacity. For tool shapes, feeds and speeds, see page 885 of the 1948 Metals Handbook.

Standard $\frac{1}{2}$ -hard free-cutting brass is favored for straight machining. It can also be knurled, thread rolled (fine pitch), roll lettered and bent, within the limits of much commercial work. For precision operations softer or lower-leaded alloys such as medium-leaded or high-leaded brass should be specified. These alloys with softer tempers also are superior for spinning, staking and expanding.

Extruded shapes or forgings in electrolytic or free-cutting copper, or architectural bronze, may offer substantial cost savings by eliminating machining operations.

Table II. Comparative Conductivity of Wrought Copper Alloys

Alloy	Rating ^(a)
Coppers	
Electrolytic (ETP)	100
Silver-bearing, 8 oz	100
Silver-bearing, 10 to 15 oz	100
Silver-bearing, 25 to 30 oz	100
Oxygen-free (OF)	100
Phosphorized (DLP)	100
Free-cutting (Se, Te or Pb)	90 to 98
Chromium coppers	80 to 90
Phosphorized (DHP)	80 to 90
Cadmium copper (1%)	80 to 90
Tellurium-nickel copper	50
Copper Alloys	
Brasses	
Phosphor bronze E	25 to 50
Naval brass	
Admiralty metal	
Phosphor bronze A, C, D	10 to 20
Aluminum bronze 5%	
Silicon bronze B	
Beryllium copper	
Cupro-nickel 30%	
Nickel silver	
Aluminum bronze (over 5% Al)	5 to 10
Silicon bronze A	

(a) All values are for the annealed condition. Cold worked alloys may be as much as 5 points lower. Compositions in Table I.

Tubular parts to be machined and lightly cold formed may be made of leaded brass containing 33.5% Zn and 0.5% Pb (Alloy 3, ASTM B135), but if these are only for machining, the lead content should be 1.5% (Alloy 4, ASTM B135). (See section on Forming.)

Standard $\frac{1}{2}$ -hard free-cutting brass rod is not suitable for riveting, severe peening by rolling or hammering, extreme cold upsetting, high-precision roll threading, knurling or similar cold working. To anneal small parts after machining may be the best solution in providing for peening or riveting operations if the design permits. Without annealing, lower-leaded alloys are best for combined machining and cold working.

Where electrical conductivity is a consideration, the cross section of a part may be such that the conductivity range of 25 to 45% of free-cutting brass is insufficient; if so, free-cutting copper is recommended (see Electrical Conductivity).

Surface Finish

Surface finish is naturally a primary consideration in copper alloys for decoration, particularly where the natural metal color is a part of the eye appeal.

Copper alloys are the only tonnage metals not white or gray. The red and yellow color range is wide—red or pink for copper; gold shades for gilding metal, commercial bronze and 85-15 brass; becoming more yellow at 80-20 (low) brass, to characteristic brass color at the 70-30 composition. A color reversal is evident at about 60-40 Cu-Zn, so Muntz metal and architectural bronze are reddish yellow and may be matched with 85-15 brass.

Copper alloys offer a noncorrosive surface for plating of tin, nickel, chromium and silver and allow thinner coatings than other metals. A base-plate of copper is unnecessary under nickel or chromium unless discolored solder joints need covering, and then only a flash plate is required. Details of pickling, cleaning and buffing are discussed completely on page 888 of the 1948 Metals Handbook.

Fused metallic enamels are used on copper, gilding metal, commercial bronze and red brass. For transparent enamels, alloys with no more than about 7% Zn should be specified; otherwise cloudiness results.

Surface finish on cold drawn parts depends largely on grain size before forming. A grain size over 0.050 mm causes "orange peel" wherever deformation is severe. Strip thickness under 0.050 in. generally is specified in grain size less than 0.040 mm. Annealing of formed parts in secondary operations to keep grain size small will reduce buffing and polishing costs.

Color match in welds may be achieved by proper selection of commercial welding rod or by using strips of the original metal. Copper requires deoxidized rods, and brasses require the original base metal except for high-zinc brasses for which low-fuming rods may suffice. Silver solder is advantageous if joints are concealed or impossible to weld. All varieties of fluxes should be removed from the surface after joining.

Copper alloys will tarnish, although aluminum bronze, cupro-nickel and nickel silver are slower to show this effect. Preservation of original color

Table III. Tensile Strength of Wrought Copper Alloys in Various Forms

Alloy	Tensile Strength, psi
Strip and Wire for Springs^(a)	
Beryllium copper	185,000 to 215,000
Phosphor bronze D	115,000 to 129,000
Phosphor bronze C	105,000 to 119,000
Nickel silver B	108,000 to 120,000
Silicon bronze A	105,000 to 113,000
Phosphor bronze A	91,000 to 105,000
Cartridge brass (70-30)	91,000 to 100,000

Plate for Pressure Vessels and Similar Containers

Aluminum bronze (91 Cu - 7 Al - 2 Fe)	70,000 to 85,000 ^(b)
Silicon bronze A	50,000 to 67,000 ^(c)
Cupro-nickel 30%	50,000 min ^(d)
Naval brass	50,000 min ^(e)
Copper	30,000 to 38,000 ^(f)

Rod and Bar Alloys^(g)

Beryllium copper (heat treated)	175,000 to 215,000
Manganese bronze B (all sizes)	115,000 min
Phosphor bronze D	70,000 to 160,000
Phosphor bronze C	60,000 to 150,000
Phosphor bronze A	55,000 to 125,000
Aluminum bronze (B150, Type II)	85,000 to 100,000
Silicon bronze A (all sizes)	85,000 min
Silicon bronze B (bolt temper)	75,000 to 85,000
Aluminum bronze (B150, Type I)	70,000 to 80,000 ^(h)
Chromium copper (heat treated)	70,000 to 80,000
Manganese bronze A	68,000 to 80,000
Naval brass	54,000 to 67,000
Phosphor bronze, grade B (leaded)	50,000 to 60,000
Free-cutting brass ($\frac{1}{2}$ hard)	45,000 to 57,000

(a) ASTM values for strip, in spring temper, except for beryllium copper which is cold worked and precipitation hardened. Fatigue limits vary with surface and temper condition and corrosion; for the indicated temper they are approximately as follows: Beryllium copper 36,000 psi, phosphor bronze C 27,000, nickel silver B 22,500, silicon bronze A 23,000, and phosphor bronze A 22,000. (b) ASTM B169 hard temper.

(c) ASTM B96 annealed. (d) ASTM B171 condenser plate under 2 in. thick. (e) ASTM B171 condenser plate under 3 in. thick. (f) ASTM B152 hot rolled temper. (g) Except where noted, all values are hard temper and show the range to be expected for various sizes. Lowest values are large sizes, highest values small sizes, in a range from 2-in. to $\frac{1}{4}$ -in. diam. (h) A popular composition is 91 Cu - 7 Al - 2 Si, sold under a variety of trade names.

requires clear coatings such as organic lacquers or transparent enamels. Outdoor exposure eventually gives a characteristic green patina on copper. Electrical contacts dictate silver plate if atmospheres are sulfur-bearing or if conditions are highly oxidizing.

The cost of a finished piece depends on both the original metal quality and the subsequent finishing operations. Proper attention to correct grain size and original metal finish will help to reduce finishing costs. Careful handling of highly finished metal during finishing operations will avoid marring.

Joining

Joining methods are governed by the alloy, its form and ultimate use. Arc welding is a popular choice for joining sheet or plate assemblies such as pressure vessels, fuel and water tanks, condensers, piping and heat exchangers for oil refining, chemical equipment

and heavy air conditioning units; silicon bronze A, cupro-nickel, aluminum bronze (7% Al, 2% Fe), copper and naval brass are conventional choices. Silver brazing is most useful for leaded alloys and small assemblies where welding is not entirely feasible.

Electrolytic tough pitch copper is difficult to weld without porosity, because it contains oxygen, hence deoxidized copper is preferred. However, electrolytic copper may be welded by gas-shielded tungsten-arc or carbon-arc methods, using rods of phosphor bronze A or one of the deoxidized coppers. Such welds may contain some fine porosity with some oxide segregation in the heat-affected zone, which may not be detrimental to the ultimate use. Where strict code requirements must be met, welding should be restricted to phosphor-deoxidized copper.

Oxygen-free copper or deoxidized copper is necessary for any operation involving reducing gases, especially hydrogen, over 700°F because of the incident reduction of copper oxide causing embrittlement. This applies to atmosphere furnace brazing, welding, torch brazing, annealing or other heating operations in reducing atmospheres.

Common joining methods for various alloys are as follows:

Resistance Welding. Conductivity under 30% is preferred, the lower the better. Cupro-nickel 30%, silicon bronze A, nickel silver, phosphor bronze and manganese brass are recommended, in descending order. Copper is very difficult to resistance weld because of its high conductivity and very strong tendency to stick to electrodes. Ordinary straight brasses are not usually resistance welded because of excessive electrode pickup. All copper and copper alloys require more machine capacity than do ferrous metals, particularly with metal conductivity above 10%.

Submerged-Arc Welding is most commonly used on silicon bronze A and 30% cupro-nickel, for which commercial fluxes are available.

Gas-Shielded Tungsten-Arc Welding is adaptable to all copper alloys except cupro-nickels, the latter requiring special wire to avoid porosity. The technique is best suited to thicknesses under $\frac{1}{4}$ in., and is especially good for copper, silicon bronze, and brasses if low-fuming rod is used.

Gas-Shielded Metal-Arc Welding is suited to the same alloys as the tungsten-arc method and is preferred on thicknesses over $\frac{1}{4}$ in. It is recommended for copper, silicon bronze and aluminum bronze (7% Al, 2% Fe).

Metal-Arc Welding is generally used only for cupro-nickels, although electrodes are available for copper, silicon bronze and phosphor bronze.

Carbon-Arc Welding is usually less suitable than other methods. As previously noted, the carbon arc may be suitable on electrolytic tough pitch copper in lower-quality applications.

Acetylene Torch Welding. Brasses are torch welded with low fuming rods if other methods are not available or are impractical.

Brazing. All alloys can be silver brazed. Copper-phosphorus and copper-silver-phosphorus alloys are self-fluxing on copper, but are not advisable for cupro-nickel. For aluminum bronze, special fluxes are available to facilitate brazing. (ASTM B260 lists brazing alloys and applications.)

Soft Soldering is suited to all copper

Table IV. Comparative Machinability of Principal Wrought Copper Alloys

Alloy ^(a)	Rating
Free-cutting brass rod	100
Free-cutting copper rod ^(b)	90
High-leaded brass	90
Architectural bronze	90
Free-cutting phosphor bronze (444)	90
Leaded copper	80
Forging brass	80
Tellurium-nickel copper	80
Leaded commercial bronze	80
Medium-leaded brass	70
Leaded naval brass	70
Aluminum-silicon bronze	60
Low-leaded brass	60
Copper	
Plain brasses	
Phosphor bronzes	under 30
Naval brass	
Silicon bronze	

(a) For nominal compositions, see Table I. (b) Containing tellurium or selenium

alloys, although special fluxes are required for aluminum bronzes.

Furnace Brazing. Atmosphere furnaces with reducing gas are widely used on copper with self-fluxing brazing alloy or with cupro-nickel 30%, using copper as the brazing filler metal. All other alloys can be furnace brazed with alloys of lower melting point, but require fluxes.

Other Considerations. Welding rods usually are the same composition as the metal to be welded, with some exceptions for copper, brasses, aluminum bronze and cupro-nickel. (ASTM B259 and B225, or AWS A5.7 and A5.6 give rod recommendations and details of applicability of welding methods.)

In electrical conductivity applications, the base metal is usually copper, and is joined by welding or silver brazing. The latter has little effect on conductivity with properly fitted joints of approximately 0.003-in. clearance.

If mechanical strength of the welded joint is important, aluminum bronze (7% Al, 2% Fe) is best and silicon bronze A is next best for pressure vessels and other stressed containers.

If cold forming is to be done, aluminum bronze (less than 8% Al), silicon bronze A, cupro-nickel or copper are favored. These alloys, as well as naval brass, manganese bronze or Muntz metal, may be hot formed.

When corrosion is a secondary factor, little difference in weld corrosion rate will be found if rods are of the same composition as the base metal. Various deoxidized copper rods are not significantly different in weld corrosion rates. Welds made with rods of low-fuming brass, naval brass, and Muntz metal which result in two-phase alloys may be subject to dezincification. Similar loss of aluminum may result if rods contain more than 8% Al or if the aluminum and other alloy content results in a two-phase composition.

Designs which result in high stresses after welding may require stress relief to avoid stress-corrosion or season cracking under certain conditions. Stress relieving is particularly important with silicon bronze A.

Corrosion Resistance

Pages 231 and 895 of the 1948 Metals Handbook give detailed discussion and definitions of types of corrosion. A few basic corrosion phenomena and suggested remedies are as follows:

Dezincification of brasses is avoided by specifying alloys with a minimum of 85% Cu or by using inhibited alloys such as inhibited admiralty or inhibited aluminum brass if copper content is less than 85%. Two-phase aluminum bronzes are susceptible to loss of aluminum.

Season Cracking or stress-corrosion cracking is rare in brasses if copper content is higher than 85%. If copper content is less than 85%, stress relieving is dictated. Leaded alloys are more susceptible than nonleaded. Silicon bronze A is susceptible but grade B ordinarily is not. Cupro-nickels, phosphor bronzes, aluminum bronzes (under 8% Al) and copper are not generally susceptible. All alloys may crack in contact with liquid metals such as mercury or molten solders if non-uniformly stressed.

Oxidizing Acids or oxidizing salts usually are strongly corrosive. Natural waters will not ordinarily corrode copper-base alloys. Silicon bronze A, aluminum bronze or copper is frequently specified for tanks and other liquid containers.

Atmospheric Corrosion produces a green patina with time, frequently desired for roofing and other architectural effects, but atmospheric corrosion is rarely a serious problem and virtually any copper may be used.

Electrolytic Action must be considered if contacting solutions are conducting. No serious electrolytic effects have been observed between copper and nickel alloys. Aluminum and iron have high electrolytic potential when coupled with copper alloys, and unfavorable surface ratios should be avoided. An example of an unfavorable surface ratio would be a steel or aluminum rivet in a copper sheet, but not the reverse.

Impingement Attack on condenser or heat exchanger tubes may be found in some power plant or marine installations. It is ascribed to the high velocity of the coolant, or to lower velocity and entrained air bubbles from pumps, leaks or incorrect water box design. Salt water velocities are more critical than fresh water; for example, about 2 ft per sec for copper in salt water and 6 ft per sec in fresh water may bring on the attack. Condensers using salt water with high velocity should specify cupro-nickel 30%, cupro-nickel 10%, inhibited aluminum brass and inhibited admiralty metal, in descending order of performance. For fresh water installations, inhibited admiralty metal is generally satisfactory.

Cost Reminders. In general, descending order of alloy cost is: beryllium copper, phosphor bronze, cupro-nickel, silicon bronze, tin brasses, brass and copper. Cost of material should be figured on an individual basis, because of density variations in alloys and differences in extras for size, gage and other factors among alloys. The relatively high value of scrap is a factor in low cost of fabricated parts.

CASTINGS

Copper alloy castings are specified when it is impractical, impossible or more costly to obtain desired shapes and properties by any other means. Irregular and often complex external and internal contours are best made by casting. A few smaller irregular shapes, such as locks, elbows and tees,

are now being made as cored forgings, but are expensive.

Compositions of casting alloys (Tables V and VI) differ from comparable wrought alloys in that they contain larger amounts of minor alloying metals and have a greater tolerance for impurities, which are not harmful within the limits of the standard specifications, such as ASTM, SAE and those of various Government departments.

The choice of an alloy for any casting usually depends on four factors: metal cost, castability, properties and final cost.

Metal Cost is a minor consideration if only a few castings are to be made. However, when a large amount of metal is required or the casting is a repetitive or highly competitive item, or when the metal cost is a major portion of the final cost of the castings, this factor becomes of prime importance. Relative cost of the various alloys, based on the price of 85-5-5-5 alloy taken as 100 (25¢ per lb as of Feb 1, 1954), is shown in Table V.

Although prices change from time to time, the relative prices remain nearly constant, with occasional minor changes in positions. In any event, final cost should be considered because the initial advantage of a lower metal cost may be entirely eliminated by an increased operating cost, resulting from some inherent property of the alloy. One such property, somewhat abstract but very real to the foundryman, is castability.

Castability

Castability should not be confused with "fluidity", which is the ability of a molten alloy to fill a mold cavity completely in every detail. Castability, on the other hand, is the ease with which an alloy responds to ordinary foundry practice, without undue attention to gating, risering, melting, sand conditions and any of the other factors involved in making good castings. Fluidity improves many of these aspects of castability.

Foundry alloys are generally classed as "high shrinkage" or "low shrinkage". To the former class belong the manganese and aluminum bronzes, silicon bronzes and brasses, and some nickel silvers. They are more fluid than the red brasses, more easily poured and give high-grade castings in sand, permanent molds, plaster, die castings and centrifugal castings. However, careful

design is necessary, to promote directional solidification, reduce abrupt changes in cross section, liberalize fillets and permit the best placement of gates and risers, and thus avoid internal shrinks and draws. Turbulent pouring must be avoided to prevent formation of dross. More liberal use of risers or exothermic compounds insures adequate metal to feed all sections. Table V includes a comparative rating of both castability and fluidity of various standard alloys, cast in sand; number 1 represents the highest castability or fluidity rating.

All copper alloys can be successfully cast in sand. Sand casting is the most economical method of making castings and has the greatest flexibility for size and shape.

Permanent mold casting is best suited for the tin, silicon, aluminum and manganese bronzes and yellow brasses. Die casting is best for yellow brasses, but increasing amounts of permanent mold alloys are also being die cast. Size is a definite limitation to both methods.

Virtually all copper alloys can be cast successfully by the centrifugal process, once the fundamentals have been mastered. Size offers no insuperable problem; castings are being made from a few ounces to over 50,000 lb, the latter being perforated cylinders for the wood-pulp and paper industry.

Plaster molds are best adapted to aluminum bronzes, yellow brasses, manganese bronzes, low-nickel bronzes, and silicon brasses and bronzes. In most of these alloys, lead should be held to a minimum, because it reacts with the calcium sulfate of the plaster to discolor the surface and increases cleaning and machining costs. Size is a limitation.

For more complete information on these casting methods, see pages 846 to 856 in the 1948 Metals Handbook and the AFS publication, "Copper-Base Alloy Foundry Practices".

Machinability

Machining follows the same general pattern as for wrought alloys. The cast alloys fall in three general groups: the first consists of copper, cupro-nickel, aluminum bronzes of low aluminum content and any other alloys which have but one soft phase in their structure. These are all "draggy" or "gummy" alloys.

Alloys of the second group contain two or more phases. Generally, the secondary phases are harder or more brittle than the matrix and result in a short chip. The silicon brasses and bronzes, higher-aluminum bronzes and higher-tin alloys belong to this group. Metallographic appearance of the manganese bronzes would seem to place them here, but they produce a long spiral chip, smooth on both sides, which does not break. High-aluminum bronzes, on the other hand, produce a long spiral chip, which is rough on the underside and breaks, thus acting like a short chip.

The third group includes any alloy to which lead has been added, either as an alloying element or to increase machinability. Their machinability, as shown in Table VII, is comparable to free-cutting brass (3% Pb, 35% Zn) as a base of 100.

General-Purpose Alloys

General-purpose alloys may be divided into two classes as to color—red and yellow. Nominal compositions, general properties and joining characteristics of these alloys are shown in Tables VI, VII and VIII.

The leaded red and semi-leaded red bronzes respond readily to ordinary foundry practice, and are rated highest in castability. Alloy 4A is the best known of this group and is generally identified as 85-5-5 or ounce metal. Together with its modification alloy 4B (83-4-6-7), it constitutes the largest tonnage of copper-base foundry alloys. They are used where moderate corrosion resistance, good machinability, moderate strength and ductility, and good castability are required. Alloy 4B has lower mechanical properties but increased machinability and lower initial metal cost.

Both alloys are used for plumbing goods, cocks and faucets, flanges, feed pumps, meter casings and parts, general household and machinery hardware and fixtures, paper machinery, hydraulic and steam valves, valve disks and seats, impellers, injectors, memo-rial markers, plaques, statuary and similar lines.

Alloys 5A and 5B are higher in lead and zinc, at the expense of copper and tin. They are lower in price, tensile strength and hardness. Their widest application is in the plumbing goods industry.

The yellow brasses (6A and 6B) are

Table V. Compositions and Relative Foundry Rating of Sand Casting Alloys

Alloy Class	Cu	Nominal Composition, %								Relative Rating, Sand Casting		
		Sn	Pb	Zn	Fe	Ni	Mn	Al	Other	Cost ^(a)	Castability ^(b)	Fluidity ^(b)
Leaded red brass	85	5	5	5	..	..	..	..	..	100	2	6
Leaded semi-red brass	81	3	7	9	..	..	..	..	..	95	2	6
Leaded semi-red brass	76	3	6	15	..	..	..	..	..	89	2	6
Yellow brass	63	1	1	35	..	..	..	..	..	91	9	8
Yellow brass with Al	63	1	1	35	..	..	..	0.25 ^(c)	..	91	4	4
Leaded yellow brass	67	1	3	29	..	..	..	0.25 ^(c)	..	85	4	4
Manganese bronze	58	..	..	Rem	1.0	..	0.5	1.0	..	103	6	2
Manganese bronze	62	..	..	Rem	2.5	..	3.5	5.5	..	128	6	2
Nickel silver	64	4	4	8	..	20	..	..	..	112	5	7
Nickel silver	66	5	1.5	2	..	25	..	..	..	118	5	7
Tin bronze	88	B	..	4	..	..	..	..	..	153	3	6
Tin bronze	88	6	2	4	..	..	..	..	..	120	3	6
Tin bronze	90	19.5	..	6	..	..	..	..	0.5 P	182	3	4
Silicon brass	81	..	..	15	..	..	..	..	4.0 Si	138	7	1
Silicon bronze	95	..	..	..	..	..	1	..	4.0 Si	118	8	3
Aluminum bronze	89	..	..	..	1	..	..	10	..	140	8	5
Aluminum bronze	81	..	..	..	4.5	4.5	..	10	..	140	8	5
High-lead tin bronze	80	10	10	..	..	..	..	..	..	124	1	6
High-lead tin bronze	70	5	25	..	..	..	..	..	..	118	1	6

(a) Relative cost, 85-5-5-5 leaded red brass = 100. (b) Relative rating 1 is highest or best possible rating. (c) Maximum

still lower in price and mechanical properties. Their main application is in die castings for plumbing goods and accessories, low-pressure valves, air and gas fittings, general hardware and ornamental castings. In general, they are best suited for small parts; on larger castings, wall thickness is kept to a minimum and phosphorus is added to increase the metal fluidity if pressure tightness is required. Aluminum (0.15 to 0.25%) is also added to yellow brasses to increase fluidity and to give a smoother surface, but aluminum additions should never be used for pressure-tight castings or in conjunction with phosphorus.

All the red and yellow alloys in this classification, when properly made and cleaned, can be plated with nickel or chromium. None of these alloys should be used above 300 to 350 F. When higher properties, increased leak tightness or higher operational temperatures are required, the higher tin bronzes are used. Nominal compositions and general properties are shown in Tables VI, VII and VIII.

Alloys without lead (1A and 1B) machine rather poorly. These are known as the "gun metals", or "Navy G" and "Modified Navy G", respectively. Alloys containing 10 to 12% Sn,

1 to 2% Ni and 0.1 to 0.3% P are known as gear bronzes. Up to 1.5% Pb is frequently added to increase machinability. The addition of lead to alloy 1B likewise increases machinability, and a concurrent decrease in tin maintains elongation. Such alloys are known as steam or valve bronze, Navy "M" (2A) or commercial "G" bronze (alloy 2B).

All alloys of this group are suitable where resistance to corrosion, leak tightness or greater strength is required at higher operating temperatures than can be tolerated with leaded red or semi-red brasses. The limiting temperature for long-time operation of Navy "M" is 550 F; for 1A, 1B and 2B it is 500 F. This is because of embrittlement produced in the higher-tin alloys, as a result of precipitation of a high-tin phase. This reaction does not occur in alloys of this type with lower tin content. (J. W. Bolton, Proc ASTM, 1935)

Nickel is frequently added to increase density and leak tightness. Alloys containing more than 3% Ni are heat treatable, but must contain less than 0.01% Pb to develop optimum properties. Nickel is added to replace part of the tin, as in the alloy 88 Cu - 5 Sn - 2 Zn - 5 Ni.

Mechanical Properties

Most alloys containing tin, lead or zinc have only moderate tensile and yield strengths, low to medium hardness and high elongation. When higher tensile or yield strength is required, the aluminum and manganese bronzes, silicon brasses and bronzes and some nickel silvers are used. Most of these alloys have the added properties of corrosion and wear resistance.

Both the aluminum and manganese bronzes range from 65,000 to 130,000 psi tensile strength, depending on composition; maximum tensile strength for aluminum bronzes is attained only after heat treatment. Both alloys may contain two phases, one relatively soft and the other hard. Since these phases differ in mechanical properties, alloys containing a mixture of them will vary in properties. Manganese bronzes which have a two-phase structure and are cooled slowly will generally have decreased tensile strength, yield strength and hardness, with increased elongation.

While both manganese and aluminum bronzes are often used for the same applications, the manganese bronzes are handled more easily in the foundry. Both these alloys belong to the so-

Table VI. Compositions of Copper Casting Alloys^(a)

Alloy ^(b)	ASTM Alloy ^(c)	Cu	Sn	Pb	Zn	Fe	Ni	Al	Mn	Other
ASTM Specification B145										
Leaded red brass	4A	85	5	5	5	....	....	....	....	....
Leaded red brass	4B	83	4	6	7	....	....	....	....	....
Leaded semi-red brass	5A	81	3	7	9	....	....	....	....	....
Leaded semi-red brass	5B	76	3	6	15	....	....	....	....	....
ASTM Specification B146										
Leaded yellow brass	6A	71	1	3	25	....	....	....	....	....
Leaded yellow brass	6B	67	1	3	29	....	....	....	....	....
ASTM Specification B143										
Tin bronze	1A	88	10	..	2	....	....	....	....	0.35 P ^(d)
Tin bronze	1B	88	8	..	4	....	....	....	....	....
Leaded tin bronze	2A	88	6	2	4	....	....	....	....	....
Leaded tin bronze	2B	87	8	1	4	....	....	....	....	....
ASTM Specification B147										
Leaded high-strength yellow brass	7A	61	0.75	0.75	35.5	1	....	0.75	0.25	....
High-strength yellow brass	8A	58	..	..	40	1.25	....	1.25	0.25	....
High-strength manganese bronze	8B	60	..	..	..	....	....	....	....	....
High-strength manganese bronze	8C	60	..	..	..	....	....	....	....	....
ASTM Specification B148										
Aluminum bronze	9A	88	....	....	..	3	....	9	....	....
Aluminum bronze, as cast	9B	89	....	....	..	1	....	10	....	....
Aluminum bronze, heat treated	9B-HT	89	....	....	..	1	....	10	....	....
Aluminum bronze, as cast	9C	85	....	....	..	4	....	11	....	....
Aluminum bronze, heat treated	9C-HT	85	....	....	..	4	....	11	....	....
Aluminum bronze, as cast	9D	81	....	....	..	4	....	11	....	....
Aluminum bronze, heat treated	9D-HT	81	....	....	..	4	....	11	....	....
ASTM Specification B144										
High-leaded tin bronze 80-10-10	3A	80	10	10	..	....	0.75 ^(e)	....	....	....
High-leaded tin bronze 83-7-7-3	3B	83	7	7	3	....	0.50 ^(e)	....	....	....
High-leaded tin bronze 85-5-9-1	3C	85	5	9	1	....	0.50 ^(e)	....	....	....
High-leaded tin bronze 78-7-15	3D	78	7	15	..	....	0.75 ^(e)	....	....	....
High-leaded tin bronze 70-5-25	3E	70	5	25	..	....	0.75 ^(e)	....	....	....
ASTM Specification B149										
Leaded nickel brass	10A	57	2	9	20	....	12	....	....	....
Leaded nickel bronze	11A	64	4	4	8	....	20	....	....	....
Nickel leaded bronze	11B	66.5	5	1.5	2	....	25	....	....	....
ASTM Specification B198										
Silicon bronze	12A	99.5 ^(f)	1 ^(g)	0.5 ^(h)	5 ^(h)	2.5 ^(h)	1.5 ^(h)	1.5 ^(h)	....	1 to 5 Si
Silicon brass	13A	99.5 ^(f)	..	1 ^(h)	12-16	....	....	....	....	2.5 to 4 Si
Silicon brass	13B	99.5 ^(f)	..	0.5 ^(h)	12-16	....	....	....	....	3 to 5 Si
Alloys Without ASTM Specifications										
Silicon-aluminum bronze	91	....	....	....	....	....	7	....	2 Si	....
Silicon-aluminum bronze	90	....	....	....	....	....	7	....	3 Si	....
Beryllium bronze	96.5	....	....	....	....	....	1.1 ⁽ⁱ⁾	2.2 to 2.8 Be	....

(a) Properties given in Tables VII and VIII. (b) Other designations used for these alloys are given as item A2 in the data compilations, pages 935 to 942, 1948 Handbook. (c) For Government specification numbers, see item A4 in each of the compila-

tions, pages 935 to 942, 1948 Handbook. (d) Composition ranges are given in current issue of each specification. (e) Optional. (f) Several compositions available will meet the mechanical requirements. (h) Maximum. (i) Total.

called "high-shrinkage" type, but the manganese bronzes have a wider solidification temperature range and hence cause fewer problems in gating and risering. Tensile strengths of 115,000 psi and 15 to 20% elongation can be obtained readily in sand castings, and considerably higher in centrifugal castings, as cast. Stresses may be relieved at 350 to 400°F. Lead may be added to the lower-strength manganese bronzes to increase machinability, but at the expense of decreased tensile strength and elongation. More than 0.1% Pb should never be present in high-strength manganese bronzes. Although manganese bronzes range from 125 to 250 Brinell, they are readily machined with proper tools.

Tin is added to the low-strength manganese bronzes to inhibit dezincification, but should be limited to 0.1% in high-strength manganese bronze, unless a great sacrifice in both strength and ductility can be accepted. Similarly, those manganese bronzes with a predominance of the beta phase are penetrated by molten metal, as in the babbitting of bushings.

Manganese bronzes are specified for marine propellers and fittings, pinions,

ball bearing races, worm wheels, gear shifter forks and architectural work—also, when high strength and hardness are required, in rolling mill screwdown nuts and slippers, bridge trunnions, gears and bearings.

Cast aluminum bronzes contain 9 to 14% Al and minor amounts of iron, manganese or nickel. They have a very narrow solidification range and, because of the greater need for adequate gating and risering, are more difficult to cast. A wide range of properties is obtainable, especially after heat treatment, but close control of composition is necessary. Like the manganese bronzes, they can develop tensile strength well over 100,000 psi, but with less ductility.

Most aluminum bronzes contain from 0.75 to 4% Fe to refine grain and increase strength. Alloys containing from 8 to 9.5% Al cannot be heat treated. They have higher tensile strength and greater ductility and toughness than any of the ordinary tin bronzes. Some of their uses are as valve nuts, cam bearings, impellers, hangers in pickling baths, agitators, crane gears and connecting rods.

The heat treatable alloys contain

from 9.5 to 11.5% Al, in addition to iron, with or without nickel or manganese. The structure of these alloys and their response to quenching and tempering resemble heat treated steels; castings are quenched in water or oil from 1600 to 1650°F and tempered at 800 to 1200°F, depending on the properties required.

The range of properties is shown in Table VII; all the maximum properties cannot be obtained in any one alloy. In general, tensile strength, yield strength and hardness vary inversely with elongation. The lower the tempering temperature, within the range specified, the higher will be the tensile strength and the lower the elongation. Some uses for these higher hardness alloys are in rolling mills, screwdown nuts and slippers, worm gears, bushings, slides, impellers, nonsparking tools, valves and dies.

Aluminum bronzes are corrosion resistant to many substances, including pickling solutions. However, aluminum may be lost preferentially, a type of corrosion similar to dezincification in the copper-zinc alloys.

Aluminum bronzes also have a high fatigue limit, considerably in excess of

Table VII. Typical Properties of Copper Casting Alloys
(See compositions in Table VI)

Alloy	0.5% Tensile Yield Strength, 1000 psi	Com- pressive Yield Strength, 1000 psi ^(a)	Tensile Strength, 1000 psi	Elong- ation, %	Brinell Hardness Number ^(b)	Shrink- age, in. per ft	Electrical Conduc- tivity, % of std Cu	Approx Melting Point, deg Fahr	Machin- ability, relative rating ^(c)
ASTM Specification B145									
Leaded red brass	16.5	11.0	36.5	32	62	7/8	15.0	1810	90
Leaded red brass	16	11.0	35.0	26	60	7/8	...	1800	90
Leaded semi-red brass	13.5	...	31.5	27	56	7/8	18.0	1750	90
Leaded semi-red brass	13	9.0	33.0	25	53	7/8	...	1725	90
ASTM Specification B146									
Leaded yellow brass	12.5	9.0	36.0	40	47	7/8	19.22	1700	80
Leaded yellow brass	11.5	9.0	35.0	46	50	7/8	22.25	1700	80
ASTM Specification B143									
Tin bronze	18.75	14.0	46.0	40	76	7/8	10	1800	50
Tin bronze	19.8	...	47.0	45	72	7/8	14	1800	50
Leaded tin bronze	17	12.0 to 15.0	43.0	52	66	7/8	14	1800	60
Leaded tin bronze	19	9.0 to 11.0	45.0	38	70	7/8	14	1800	60
ASTM Specification B147									
Leaded high-strength yellow brass .	23	22.0	65.0	35	110 ^(d)	1/4	22	1675	60
High-strength yellow brass	25	24.0	72.0	25	130 ^(d)	7/8	22	1675	30
High-strength manganese bronze	57	50.0	98.0	20	188 ^(d)	7/8	7 to 8	1700	30
High-strength manganese bronze	70	60.0	115.0	16	225 ^(d)	7/8	8.0	1700	20
ASTM Specification B148									
Aluminum bronze	26.5	18.0	75.0	30	120 ^(e)	1/2	13	1900	20
Aluminum bronze, as cast	25 to 33	...	68 to 77.0	15 to 25	120 to 160 ^(e)	1/2	14	1900	35
Aluminum bronze, heat treated	37 to 55	...	82 to 90.0	2 to 30	150 to 230 ^(e)	...	...	1900	..
Aluminum bronze, as cast	25 to 37	22.0	65 to 90.0	10 to 28	125 to 175 ^(e)	1/2	12	1900	20
Aluminum bronze, heat treated	35 to 50	28 to 50.0	82 to 98.0	4 to 25	150 to 220 ^(e)	...	...	1900	..
Aluminum bronze, as cast	40 to 60	...	100 to 110	5 to 18	175 to 230 ^(e)	1/4	9	1900	20
Aluminum bronze, heat treated	55 to 85	...	110 to 128	3 to 12	210 to 270 ^(e)	...	...	1900	..
ASTM Specification B144									
High-leaded tin bronze 80-10-10	18	15.0	41.0	28	69	7/8	10	1760	80
High-leaded tin bronze 83-7-7-3	18	14.0	39.0	34	70	7/8	12	1750	70
High-leaded tin bronze 85-5-9-1	16	13.0	34.0	25	63	7/8	...	1750	70
High-leaded tin bronze 78-7-15	14	14.0	32.0	24	57	7/8	11	1700	80
High-leaded tin bronze 70-5-25	11	13.0	21.0	15	50	7/8	...	1650	90
ASTM Specification B149									
Leaded nickel brass	18	8.0	35.0	24	65	7/8	6	1800	70
Leaded nickel bronze	22	...	47.0	22	80	7/8	5	...	..
Nickel leaded bronze	35	...	60.0	15	135	7/8	4	...	..
ASTM Specification B198									
Silicon bronze	18 to 28	...	50 to 60.0	16 to 25	60 to 100	...	...	...	..
Silicon brass	21 to 33	...	50 to 70.0	20 to 50	70 to 130	...	...	...	..
Silicon brass	29 to 35	...	60 to 75.0	17 to 50	65 to 125	...	...	...	..
Alloys Without ASTM Specifications									
Silicon-aluminum bronze	29	...	70.0	20	135	7/8	7	1800	50
Silicon-aluminum bronze	38 to 41	...	75 to 84.0	5 to 14	165 to 190	7/8	6	1800	50
Beryllium bronze	85 to 100	...	90 to 125	0 to 4	325 to 425	1/4	18 to 25	1930	20 to 40

(a) Stress for permanent set of 0.001 in. per in. (b) 500-kg load, 10-mm ball. (c) Free cutting brass = 100. (g) 3000-kg load, 10-mm ball.

manganese bronze or any other cast copper alloy. Unlike the Cu-Zn or Cu-Sn-Pb-Zn alloys, the mechanical properties of aluminum and manganese bronzes do not decrease much with increase in cross section of the castings. This is because of a narrow freezing range, which results in a denser structure when castings are properly designed and properly fed.

While manganese bronzes become hot short above 450°F, aluminum bronzes can be used as high as 750°F for a short time without much loss of strength. For example, room-temperature tensile strength of 78,000 psi declines to 76,700 at 500°F; 67,000 at 750°F, and 58,000 at 1000°F; and elongations change from 28% to 32, 35 and 25%, respectively.

Unlike manganese bronzes, many aluminum bronzes increase in yield strength and hardness on slow cooling but tensile strength and elongation decrease simultaneously. While some manganese bronzes precipitate a relatively soft phase during slow cooling, aluminum bronzes precipitate a hard constituent rather rapidly within a narrow temperature range, 1050 to 900°F. Hence, large castings or those cooled slowly will have properties different from those cooled at a faster rate. The same phenomenon occurs on aging the heat treated aluminum bronzes. Cooling slowly through the critical temperature range after quenching, or aging at temperatures within this range, will decrease elongation. The addition of 2 to 5% Ni to aluminum bronzes will greatly mitigate this effect of cooling rate.

The variation in properties in these two alloys caused by section size (slow cooling) is not a result of the same factor as in the tin bronzes or the leaded red brasses. In the latter alloys, the decrease in properties in large sections is caused by the wide solidification range which, when any dissolved gases are present, increases the difficulty in adequately feeding these sections. Consequently, these alloys show far greater decrease in properties, as section size is increased, than do the manganese or aluminum bronzes. Data on the decrease in properties of tin bronzes and leaded red brasses, with an increase in cross section, are often conflicting and misleading.

Nickel brasses, silicon brasses and bronzes, while generally higher in strength than red metal alloys, are used more for their corrosion resistance and are discussed under that heading.

Bearing and Wear Properties

Copper alloys have long been used for bearings because of their combination of moderate-to-high strengths, corrosion resistance, wear resistance or self-lubrication. The choice of an alloy depends on corrosion, fatigue, rigidity of backing material, lubrication, thickness of bearing material, load, speed of rotation, atmospheric conditions and other factors. They may be used as cast plain bearings, cast on steel backs, cast on rolled strip, as sintered powder shapes or they may be sintered on a backing material.

Bearing and wear-resistant alloys may be divided into three groups: phosphor bronzes (Cu-Sn); copper-tin-lead (low zinc); manganese, aluminum and silicon bronzes (Table VI).

Phosphor bronzes (Cu-Sn or Cu-Sn-

Table VIII. Joining Characteristics of Copper Casting Alloys
(See compositions in Table VI)

Alloy	Joining Characteristics ^(a)					
	Oxy-acetylene Weldability	Carbon-Arc Weldability	Metal-Arc Weldability	Arc Weldability	Braze- ability	Solder- ability
ASTM Specification B145						
Leaded red brass	4	4	3	2		2
Leaded red brass	4	4	3	2		2
Leaded semi-red brass	4	4	3	2		2
Leaded semi-red brass	4	4	3	2		2
ASTM Specification B146						
Leaded yellow brass	4	4	4	3		2
Leaded yellow brass	4	4	4	3		2
ASTM Specification B143						
Tin bronze	3	3	3	2		2
Tin bronze	3	3	3	2		2
Leaded tin bronze	3	3	3	3		3
Leaded tin bronze	3	3	3	3		3
ASTM Specification B147						
Leaded high-strength yellow brass	4	4	4	3		2
High-strength yellow brass	2	2	2	4		2
High-strength manganese bronze 2	2	2	2	4		2
High-strength manganese bronze 2	2	2	2	4		3
ASTM Specification B148						
Aluminum bronze	2	2	2	4		4
Aluminum bronze, as cast	2	2	2	4		4
Aluminum bronze, as cast	2	2	2	4		4
Aluminum bronze, as cast	2	2	2	4		4
ASTM Specification B149						
Leaded nickel brass	4	4	4	3		2
Alloys Without ASTM Specifications						
Silicon-aluminum bronze	2	3	3	3		4
Silicon-aluminum bronze	2	3	3	3		4
Beryllium bronze	4	3	3	3		NG

(a) Relative ratings: 1 = best; 2 = good; 3 = fair; 4 = poor; NG = no good

Pb alloys deoxidized with phosphorus have residual phosphorus ranging from a few hundredths of 1% (for deoxidation and slight hardening) to a maximum of 1% where it imparts great hardness. Nickel is often added to refine the grain and disperse the lead. Copper-tin bearings have high resistance to wear, high hardness and moderately high strength. The 11% Sn alloy is so widely used for all types of gears that it is called gear bronze.

Bronzes of higher tin content (17 to 20%) go into bridge turntables where loads are high and movement is slow. A maximum load of 2500 psi is permitted for the 17% Sn alloy and 3500 psi for the 20% alloy. They contain high phosphorus to impart hardness and low zinc (0.25% max), to prevent seizing; they are very brittle and are being replaced by manganese and aluminum bronzes for this use.

The Cu-Sn-Pb alloys are used where a softer metal is required at light to moderate speeds, and loads not in excess of 800 psi. These include alloys 3A, 3B and 3C of ASTM B144. Alloy 3A, known as 80-10-10, is an excellent general bearing alloy, suitable under the above-mentioned conditions or when lubrication may be deficient. It finds wide application in machine tools, electrical and railroad equipment, in steel mill machinery and automotive vehicles. Alloys 3B and 3C are less costly and are used largely in maintenance service. Alloys of composition similar to 3D and 3E are used where high loads are encountered under conditions of poor or no lubrication, or

under corrosive conditions, such as in mining equipment (pumps and car bearings), or in dusty atmospheres, as in stone crushing and cement plants. The permissible load on these alloys varies directly with the tin content and inversely with the lead. They replace the copper-tin bronzes where conditions of operation are unsuitable for the latter.

High-strength manganese bronzes give high tensile strength, hardness and resistance to shock. Large gears, bridge turntables (slow motion and high compression), roller tracks for anti-aircraft guns, and recoil parts of heavy ordnance are typical.

Aluminum bronzes with 8 to 9% Al are used widely for bushings and bearings in light or high-speed work. As the aluminum is increased to 11%, the alloys, both as-cast and heat treated, are suitable for heavier service, such as valve guides, rolling-mill bearings, screwdown nuts, slippers and in precision machines. As aluminum content increases above 11%, hardness increases and elongation decreases to low values. Such alloys are well suited for guides and aligning plates, where wear is excessive. Above 13% Al, 300 Brinell is exceeded, but the alloys are brittle. Such alloys are suitable for dies and installations involving no impact.

Aluminum bronze in general has the advantage over manganese bronze of a considerably higher fatigue limit and freedom from galling. Manganese bronze, on the other hand, has great toughness for equivalent tensile strength and requires no heat treatment.

Corrosion Resistance

The use in plumbing goods and general industrial applications is in part attributable to the inherent corrosion resistance of copper itself. The addition of tin, lead, silicon and aluminum enhances this property in many alloys, and improves mechanical properties.

The high-tin bronzes resist a wide range of solutions, of which the following are representative:

Acetic acid	Sea water
Acetic anhydride	Brine
Acetone	Sulfuric acid
Aluminum chloride	Sodium sulfite
Ammonium chloride	Sulfurous acid
Bromides	Sodium phosphate
Chlorine water	Sodium nitrate
Copper sulfate	Sodium carbonate
Bromine and its acids	Citric acid
Mine water	Amyl acetate

They are also used extensively for marine hardware and fittings, to combat corrosion by salt water or combined wear and corrosion.

Aluminum bronzes are likewise resistant to many of the above conditions, are especially resistant to sulfuric acid, and have considerable utility in pickling equipment. Other uses are in processes handling alkaline solutions, petroleum sludges, wool washing machinery, combinations of heat, moisture and industrial fumes. The alloy containing 4 to 5% Fe, 4 to 5% Ni and 10% Al is being used in increasing amounts for large marine propellers because of its high corrosion resistance.

Aluminum bronze is used in aircraft construction and in anti-aircraft ordnance, where corrosion resistance is coupled with bearing properties and mechanical strength.

Low-strength manganese bronze is usually specified for marine propellers and marine hardware. Up to 1% Sn is generally added to inhibit or reduce dezincification in the beta phase of the alloy. For this reason, a considerable amount of the soft alpha phase should be present, which automatically excludes the use of most

Table IX. Composition and Properties of Heat Treated Copper Alloy Castings of High Strength and Conductivity

Composition, %	Tensile Strength, psi	Yield Strength, psi	Elongation, %	Brinell Hardness	Electrical Conductivity, % IACS
99.85 Cu	28,000	18,000	40	38	80
0.80 Cr, 0.08 Si	50,000	32,000	16	100	80
0.60 Si, 2.40 Co	65,000	50,000	15	120	65
0.60 Si, 3.00 Ni	75,000	60,000	15	140	45
2.60 Co, 0.40 Be	90,000	70,000	10	220	45

high-strength manganese bronzes. Nickel brasses and bronzes are widely accepted by the food, dairy and allied industries, as well as in pharmaceutical, dental and hospital equipment. Included are plumbing fixtures, impellers, stirrers, mixers, bearings, instruments and general accessories which must resist food acids or medicinal stains and be germicidally clean.

Nickel imparts a white color to copper-zinc alloys at about 12%, and they become increasingly silvery as the content increases.

Although Table VI includes only ASTM alloys, a number of others have high strength and good bearing properties, in addition to corrosion resistance. Thus, silicon, iron and manganese are frequently added to some of the nickel silvers to improve mechanical properties. Silicon bronzes, silicon-aluminum bronzes and silicon brasses are being used as valve stems, valves for special corrosive conditions, naval hardware and in many chemical plants. They have good corrosion resistance in the absence of oxygen.

Electrical and Thermal Conductivity

Electrical and thermal conductivity of any casting will invariably be lower than for wrought metal of the same composition. Copper castings are used in the electrical industry for current-carrying capacity, and as water-cooled parts of melting and refining furnaces for high heat conductivity. However,

sound copper castings, with at least 85% electrical or heat conductivity, are difficult to make. The ordinary deoxidizers (silicon, tin, zinc, aluminum or phosphorus) cannot be used because small residual amounts lower the electrical and heat conductivities drastically. Calcium boride or metallic lithium will help to produce sound castings with high conductivities. Such castings are used in the steel industry as bosh plates, tuyeres, tuyere coolers, "monkey" coolers, mantle plates, hot blast valves, seats and gates, and jackets for charging doors. Similarly, water-cooled cast copper electrode holders are made for electric furnace use.

Cast copper is soft and low in strength. Increased strength and hardness with good conductivity may be obtained with heat treated alloys containing silicon, cobalt, chromium, nickel and beryllium in various combinations.

These alloys, however, are expensive and less readily available than the standardized alloys. Special precautions must be taken with some of them in melting, to avoid undue loss of the alloying elements and accompanying changes in the heat treating characteristics. Table IX shows some of the properties obtained on these alloys in the heat treated condition.

In general, copper castings are difficult to machine. When increased machinability is required for copper castings in blast furnace parts, 1% Sn is added. For this application, the accompanying decrease in conductivity is not considered excessive.

Properties of Copper and Copper Alloys

AN INDEX TO DATA TABULATED IN THE 1948 METALS HANDBOOK

Pure Copper	903	Cu - 1.5 Si (Silicon Bronze, Type B).....	927
99.92 Cu - 0.04 O (Electrolytic Tough Pitch Copper).....	904	Some Properties of Aluminum Bronzes.....	928
99.94 Cu - 0.02 P (Deoxidized Copper)	907	95 Cu - 5 Al (5% Aluminum Bronze).....	928
Wrought Alloys			
Some Properties of Copper-Zinc Alloys.....	909	92 Cu - 8 Al (8% Aluminum Bronze).....	929
95 Cu - 5 Zn (Gilding Metal).....	910	Cu - 10 Al (10% Aluminum Bronze).....	930
90 Cu - 10 Zn (Commercial Bronze).....	911	82.5 Cu - 10 Al - 5 Ni - 2.5 Fe (Aluminum Bronze).....	932
85 Cu - 15 Zn (Red Brass).....	912	82.5 Cu - 2 Be - 0.25 Co (or 0.35 Ni) (Beryllium Copper).....	934
80 Cu - 20 Zn (Low Brass).....	914	Casting Alloys	
70 Cu - 30 Zn (Cartridge Brass).....	915	88 Cu - 6 Sn - 1.5 Pb - 4.5 Zn (Leaded Tin Bronze).....	935
65 Cu - 35 Zn (Yellow Brass).....	917	87 Cu - 8 Sn - 1 Pb - 4 Zn (Leaded Tin Bearing Bronze).....	936
60 Cu - 40 Zn (Muntz Metal).....	917	85 Cu - 5 Sn - 9 Pb - 1 Zn (High-Leaded Tin Bronze).....	936
89 Cu - 9.25 Zn - 1.75 Pb (Leaded Commercial Bronze).....	918	83 Cu - 7 Sn - 7 Pb - 3 Zn (High-Leaded Tin Bronze).....	936
64.5 Cu - 33 Zn - 0.5 Pb (Low-Leaded Brass).....	918	80 Cu - 10 Sn - 10 Pb (High-Leaded Tin Bronze).....	936
67 Cu - 32.5 Zn - 0.5 Pb (Low-Leaded Brass Tube).....	918	78 Cu - 7 Sn - 15 Pb (High-Leaded Tin Bronze).....	937
64.5 Cu - 34.5 Zn - 1.0 Pb (Medium-Leaded Brass).....	918	70 Cu - 5 Sn - 25 Pb (High-Leaded Tin Bronze).....	937
62.5 Cu - 35.75 Zn - 1.75 Pb (High-Leaded Brass).....	918	85 Cu - 5 Sn - 5 Pb - 5 Zn (85 - 5 - 5 - 5).....	937
62.5 Cu - 35 Zn - 2.5 Pb (Extra-High-Leaded Brass).....	919	83 Cu - 4 Sn - 6 Pb - 7 Zn (Leaded Red Brass).....	938
61.5 Cu - 33.5 Zn - 3 Pb (Free-Cutting Brass).....	919	81 Cu - 3 Sn - 7 Pb - 9 Zn (Leaded Semi-Red Brass).....	938
60 Cu - 39.5 Zn - 0.5 Pb (Leaded Muntz Metal).....	920	76 Cu - 3 Sn - 6 Pb - 15 Zn (Leaded Semi-Red Brass).....	938
60.5 Cu - 38.4 Zn - 1.1 Pb (Free-Cutting Muntz Metal).....	920	71 Cu - 1 Sn - 3 Pb - 25 Zn (Leaded Yellow Brass).....	938
60 Cu - 38 Zn - 2 Pb (Forging Brass).....	920	66 Cu - 1 Sn - 3 Pb - 30 Zn (Leaded Yellow Brass).....	939
57 Cu - 40 Zn - 3 Pb (Architectural Bronze).....	920	60 Cu - 1 Sn - 1 Pb - 38 Zn (Leaded Yellow Brass).....	939
71 Cu - 28 Zn - 1 Sn (Admiralty Metal).....	920	62 Cu - 26 Zn - 3 Pb - 5.5 Al - 3.5 Mn (High-Strength Yellow Brass).....	939
60 Cu - 39.25 Zn - 0.75 Sn (Naval Brass).....	921	58 Cu - 39.25 Zn - 1.25 Fe - 1.25 Al - 0.25 Mn (High-Strength Yellow Brass).....	940
60 Cu - 37.5 Zn - 1.75 Pb - 0.75 Sn (Leaded Naval Brass).....	922	50 Cu - 0.75 Sn - 0.75 Pb - 37 Zn - 1.25 Fe - 0.75 Al - 0.5 Mn (Leaded Manganese Bronze).....	940
58.5 Cu - 39 Zn - 1.4 Fe - 1 Sn - 0.1 Mn (Manganese Bronze).....	922	66 Cu - 5 Sn - 1.5 Pb - 2 Zn - 25 Ni (Nickel Silver).....	940
76 Cu - 22 Zn - 2 Al (Aluminum Brass).....	923	64 Cu - 4 Sn - 4 Pb - 8 Zn - 20 Ni (Nickel Silver).....	940
95 Cu - 5 Sn (Phosphor Bronze, 5% - Grade A).....	923	57 Cu - 2 Sn - 9 Pb - 20 Zn - 12 Ni (Nickel Silver).....	941
92 Cu - 8 Sn (Phosphor Bronze, 8% - Grade C).....	923	60 Cu - 3 Sn - 5 Pb - 16 Zn - 10 Ni (Leaded Nickel Brass).....	941
90 Cu - 10 Sn (Phosphor Bronze, 10% - Grade D).....	924	89 Cu - 1 Fe - 10 Al (Aluminum Bronze).....	941
98.75 Cu - 1.25 Sn (Phosphor Bronze, 1.25% - Grade E).....	924	87.5 Cu - 3.5 Fe - 9 Al (Aluminum Bronze).....	942
70 Cu - 30 Ni (Cupro-Nickel, 30%).....	925	86 Cu - 4 Fe - 10 Al (Aluminum Bronze).....	942
65 Cu - 18 Ni - 17 Zn (Nickel Silver, 18% - Alloy A).....	925	79 Cu - 5 Fe - 11 Al - 5 Ni (Aluminum Bronze).....	942
55 Cu - 27 Zn - 18 Ni (Nickel Silver, 18% - Alloy B).....	926		
Cu - 3 Si (Silicon Bronze, Type A).....	926		

Magnesium and Magnesium Alloys

By the ASM Committee on Magnesium

THE MAGNESIUM SECTION of the 1948 ASM Metals Handbook, pages 967 to 1024, is still accurate in most details. However, additional information is now available concerning alloys and processes that have attained industrial use during the past six years. This article supplements the 1948 Magnesium Section by summarizing the most important of the new data on production, processing, application and alloy properties, in the order named.

Production and Use

Annual production of primary magnesium in the United States reached 106,000 tons in 1952 and declined to 92,000 tons for 1953 (Fig. 1). The government-operated magnesium plants, reopened in 1951, were closed in 1953. Consumption in 1953 was 26,000 tons; the remainder went to the Government stockpile. The consumption of all magnesium products has increased

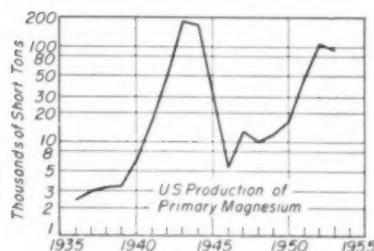


Fig. 1. Production of Primary Magnesium in the United States

steadily since 1946, the postwar low period. Distribution among products in 1948 and 1953 is compared in Table I. The greatest percentage increases have been in permanent mold and die castings. Sand castings increased the most in tonnage.

Cast products amount to about 65% of the total. The industry now includes over 75 sand and permanent mold foundries and more than 30 die casters. Five companies produce extrusions (not including aluminum extruders also able to work magnesium); four companies

operate rolling mills, and three make magnesium forgings.

A notable improvement in grain refinement by carbon inoculation has been made since 1948. Improved foundry techniques have also enabled the production of large, intricate, thin-walled castings, utilized in many aircraft and airborne products. Forging applications have not increased significantly since 1948; utilization of sheet has increased steadily as fabricators have become more familiar with the use of heated tools.

During the past five years five new alloys have been introduced: ZK60A for extrusions and forgings; ZK51A for

castings used at normal temperature; and EK30A, EK41A and EZ33A for castings used at elevated temperatures. Data on these new alloys are tabulated on page 78; new information on alloy AZ91C is given on page 79.

A standard system of alloy designation, adopted in 1948, is explained in Table II. The designation system works as follows: Consider the magnesium alloy designated AZ91C-T4, whose standard composition and typical properties appear on page 79. The first part of the designation, AZ, signifies that aluminum and zinc are the two principal alloying elements. The second part of the designation, 91, means aluminum and zinc are present in rounded-off percentages of 9 and 1%, respectively. The third part, C, indicates that this is the third alloy standardized with 9% Al and 1% Zn as the principal alloying additions. The fourth part, T4, notes that the alloy is in the solution treated condition.

Processing

With the exceptions discussed below, magnesium and magnesium alloys are fabricated by methods described on pages 978 to 991 of the 1948 Metals Handbook.

Impact Extrusion methods are now used for making some small, symmetrical, tubular parts. Any sturdy, well guided press delivering about 30 tons per sq in. pressure, will turn out impact extrusions at rates up to 100 pieces per min.

Commercial wrought magnesium alloys in Fig. 2 can be impact extruded; pressure requirements at 450 to 750°F are shown on the graph. Temperatures as low as 300°F are commonly used. Impact extrusions are practical for tubular products with wall thickness from 0.02 to 0.10 in. and length-to-diameter ratios up to 8 to 1. Reduction in area in this one-step

Table II. Standard Four-Part System for Alloy Designation (ASTM)^(a)

First Part	Second Part	Third Part	Fourth Part
Indicates the two principal alloying elements	Indicates the amounts of the two principal alloying elements	Distinguishes between different standard alloys with the same rounded-off percentages of the two principal alloying elements	Indicates condition and properties
Consists of two code letters representing the two main alloying elements arranged in order of decreasing percentage (or alphabetically if percentages are equal)	Consists of two whole numbers corresponding to rounded-off percentages of the two main alloying elements and arranged in same order as the alloy designations in the first part	Consists of a letter of the alphabet assigned in order as compositions become standard	Consists of a letter followed by a number. (Separated from the third part of the designation by a hyphen)

Alloy Designations

Code Letter	Element	Code Letter	Element
A	Aluminum	M	Manganese
B	Bismuth	N	Nickel
C	Copper	P	Lead
D	Cadmium	Q	Silver
E	Rare Earth	R	Chromium
F	Iron	S	Silicon
H	Thorium	T	Tin
K	Zirconium	Z	Zinc
L	Beryllium		

Whole numbers

Letters of alphabet except I and O

F—As fabricated^(b)
O—Annealed
H24—Strain hardened and partially annealed
T4—Solution heat treated
T5—Artificially aged only
T6—Solution heat treated and artificially aged

(a) This system is standard for both magnesium and aluminum alloys; thus, designation should be preceded by the name of the base metal unless base metal is obvious. (b) Temper designation system has been adopted by Aluminum Association and Magnesium Association but not as yet by the ASTM. (c) Only those temper designations presently used in magnesium alloy standards are listed here.

Supplements the Magnesium Section of the 1948 ASM Metals Handbook, pages 967 to 1024

Table III. Anodic Treatments for Magnesium Alloys

Acid Bath Treatment		
Electrolyte		
Ammonium acid fluoride	240 to 300 g	
Sodium dichromate	100 g	
Phosphoric acid (85%)	90 ml	
Water	to make 1000 ml	
Operating Conditions		
Current density	5 to 50 amp per sq ft	
Time	300 to 500 amp-min per sq ft	
Temperature	current density in amp per sq ft	
Voltage	160 to 180 F	
	up to 110 ac or dc	
HAE Alkaline Bath Treatment		
Electrolyte		
Potassium hydroxide	120 g	
Aluminum hydroxide (trihydrate)	30 g	
Potassium fluoride	33.8 g	
Trisodium phosphate	33.8 g	
Potassium manganate	18.8 g	
Water	to make 1000 ml	
Operating Conditions		
Current density	15 amp per sq ft preferred 900 amp-min per sq ft	
Time (general use)	current density in amp per sq ft 45 amp-min per sq ft	
Time (paint base)	current density in amp per sq ft up to 90 ac	
Voltage		
Note:	Under certain conditions, a 0.0003-in. softer HAE coating can be produced which appears to have corrosion resistance approaching that of thicker, harder coatings.	

process is usually 85 to 95%. Practical tolerances on wall thickness are from ± 0.002 in. on thinnest walls, to ± 0.005 in. on the thickest sections extruded.

Welding is mostly inert-gas-shielded arc welding, using tungsten electrodes. Weld efficiencies of 80% of the parent stock are common. Shielded-arc welding with consumable electrodes is feasible for magnesium more than $\frac{1}{8}$ in. thick. Resistance welding, especially spot welding, is economically feasible.

Adhesive Bonding of magnesium is now an established method of joining. It saves weight, the joints are stronger in fatigue than mechanical joints, and corrosion at faying surfaces is also eliminated.

Machining techniques described in the 1948 Handbook are now used extensively. Cutting of magnesium with carbide saws, routers, milling cutters and shapers at 8000 ft per min is possible; power requirements are about 1/6 those for mild steel. Sharp cutting edges and polished tool faces are required for best results.

Cleaning and Finishing

The acetic acid pickle has been replaced by the following acetic-nitrate pickle, at 68 to 77 F:

Glacial acetic acid (CH_3COOH)	.25½ fl oz
Sodium nitrate (NaNO_3)	6½ oz
Water	To make 1 gal

Usual treating time is 30 to 60 sec. This pickling solution can be contained in aluminum, ceramic or rubber-lined tanks.

Anodic Treatments. Two new anodic treatments are available for magnesium, the acid bath and the HAE alkaline bath. Both are superior to the dichromate treatment when maximum corrosion resistance and paint adhesion are desired. The treatments are self-cleaning and require no pre-pickle, as the high voltage forms the coating under contaminants and lifts them from the surface. Corrosion product, graphite, mill scale, heavy metal impurities and other foreign elements are

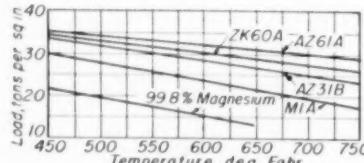


Fig. 2. Pressure Requirements for Impact Extruding Magnesium and Four Magnesium Alloys with Graphite Lubricant and 85% Reduction in Area

all removed during the process. Nevertheless, to avoid contaminating the bath excessively, particularly dirty or greasy surfaces should be given some precleaning.

Both coatings provide an excellent base for paint and for oil or wax coatings. They are resistant to many chemicals and have good abrasion resistance; the HAE coating is superior in this respect. For resistance to mildly corrosive environments the HAE coatings should be dipped for 25 to 30 sec in a hydrofluoric acid solution (1/3 HF by vol), rinsed and aged at 170 F in 90% relative humidity for 3 to 8 hr.

Coating bath compositions and operating conditions for the two anodic treatments are shown in Table III; both anodic treatments, so applied, increase dimensions by about 0.001 in. per surface. If desired, the coating may be held to as little as 0.0002 in. Under certain conditions, a 0.0003-in. softer HAE coating can be produced which appears to have corrosion resistance approaching that of thicker, harder coatings.

Caustic Anodizing, described on page 993 of the 1948 Handbook, is now little used; dyeing of the coating for commercial uses has not been practical.

Electroplating. A commercially acceptable electroplating process has been developed for magnesium alloys. Its success depends almost entirely on adhesion and uniformity of the initial zinc immersion coating and proper formulation and control of the copper strike bath.

Table IV. Zinc Immersion Coating Solution

	oz	g per l
Zinc sulphate monohydrate ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$)	6	45
Tetrasodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$)	28	210
Ether:		
Potassium fluoride (KF) or Sodium fluoride (NaF)	0.94 0.67	7 5
Either:		
Potassium carbonate (K_2CO_3) or Sodium carbonate (Na_2CO_3)	0.67	5
Water	to make 1 gal	

Table V. Copper Striking Bath Compositions

	oz	g per l
Bath A		
Copper cyanide (CuCN)	5.5	41.25
Sodium cyanide (NaCN)	6.8	51.0
Sodium carbonate (Na_2CO_3)	4.0	30.0
Rochelle salt ($\text{KNaC}_2\text{H}_4\text{O}_6 \cdot 4 \text{ H}_2\text{O}$)	6.0	45.0
Sodium hydroxide (NaOH)	1.0	7.5
Free cyanide	0.75	5.6
Water	to make 1 gal	
Bath B		
Copper cyanide (CuCN)	3.5	26.25
Potassium cyanide (KCN)	6.1	45.75
Potassium carbonate (K_2CO_3)	2.0	15.0
Potassium hydroxide (KOH)	1.0	7.5
Potassium fluoride (KF)	4.0	30.0
Free cyanide	1.0	7.5
Water	to make 1 gal	

For decorative chromium plating (successive Cu, Ni, Cr) minimum plate thicknesses should be 0.00075 to 0.001 in. for interior use, 0.00125 for mild exterior service, 0.0015 for average exterior and 0.002 in. for severe exterior exposure. When nickel is not used, the total plate thickness should be increased 25% to provide corrosion resistance equal to the Cu-Ni-Cr plate.

The five basic steps for electroplating magnesium and magnesium alloys are: surface conditioning, activating, zinc immersion coating, copper striking, and standard plating procedure to obtain the final coating.

Surface Conditioning. All parts must be pickled or mechanically polished. Before pickling, oily matter must be cleaned off. Blast cleaned surfaces are highly reactive and unsuitable for plating unless pickled after blasting.

Activating. To activate magnesium surfaces that will receive the zinc coating, parts are immersed 2 min at 70 to 90 F in the following bath: concentrated phosphoric acid (85% H_3PO_4), 1.6 pints; sodium, potassium or ammonium acid fluoride (NaHF_2 , KHF_2 or NH_4HF_2), 13½ oz; water, to make 1 gal. This solution removes normal surface contamination from magnesium without a roughening etch, and activates the surface to receive the zinc immersion coating.

Zinc Immersion Coating is applied by the solution given in Table IV. The bath is prepared by first dissolving the zinc sulfate monohydrate in water at room temperature. The solution is then heated to 140 to 180 F and the tetrasodium pyrophosphate added. A fluffy precipitate forms and dissolves after further stirring for 5 min or longer, depending on temperature and agitation. After the precipitate is completely dissolved, the fluoride is added, then the carbonate to adjust the pH, which may range between 10.0 and 10.6, with 10.2 to 10.4 preferred (colorimetric determinations; electrometric values with a glass electrode should be 0.5 pH lower). More or less carbonate may be required than the quantity

shown, to obtain the proper pH in the above range. Carbonate should be added slowly and pH measurements made intermittently.

The bath is operated at 175 to 185 F with mild agitation. Parts are immersed for 3 to 10 min; optimum time is 3 min for M1A alloy and about 5 min for other magnesium alloys. Time will vary with temperature, alloy and freshness of the bath, but should be only long enough to cover the part completely with a zinc deposit. Beyond this point, the zinc may loosen, which will result in poor adhesion of subsequent electrodeposits. Immersion is followed by cold water rinsing only.

Copper Striking. Immediately after being rinsed, the zinc coated parts are given a copper strike in one of the copper cyanide baths defined in Table V. These are operated at 130 to 150 F, with cathode agitation preferred.

With either bath, a high current density of 30 to 40 amp per sq ft is applied for the first 30 to 60 sec if deeply recessed parts are to be plated. Prolonged striking at high current density should be avoided, as it may cause inferior adhesion and subsequent blistering. After the first 30 to 60 sec deposition, current density is decreased to 15 to 25 amp per sq ft, and plating is continued for 5 min, or longer if maximum brightness is desired. Average parts, not deeply recessed, do not require a high initial current density.

Periodic current reversal is advantageous. Using a 15-sec forward and 3-sec reverse plating cycle, bright smooth deposits may be obtained, eliminating the need for further copper plating. With periodic reversal, it is best to plate the first 30 to 60 sec on the forward cycle, and then to apply alternating forward and reverse cycle. This allows an initial layer of copper to build up before deplating occurs, assuring best adhesion.

After deposition of at least 0.0005 in. of copper, the parts are immersed in any conventional bath for electrodeposition of nickel, chromium, silver, gold, cadmium or other desired metal. When cyanide baths are used for final plating, 0.0001 in. of copper is sufficient.

Painting. For most commercial products, the polyvinyl butyral primers, with or without phosphoric acid activating agent, adhere well to bare or poorly chemically treated magnesium. The phosphoric acid content of wash primers must be kept low to prevent formation of hydrogen, which is trapped in the primer film as a blister.

Finishes containing the epichlorhydrin bisphenol resins adhere well to bare magnesium and have good resist-

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ance to alkaline solutions; hence they protect magnesium from galvanic corrosion. Vinyls are also outstanding in this respect. Further information on painting is given on page 993 of the 1948 Handbook.

Application, Design and Selection

Service experience in military aircraft, emphasis on weight saving in military equipment generally, and development of new alloys have resulted in increased use of magnesium since the year 1948.

Alloy ZK60A has provided extrusions and forgings of higher strength at room temperature; ZK51A is the analogous alloy for castings. The new alloys EK30A, EK41A and EZ33A, containing rare earth metals, extend the useful temperature range for magnesium alloys to about 600 F.

Fatigue Considerations influence design for magnesium increasingly because the static properties of the stronger magnesium alloys have been improved more than their fatigue strength. Representative fatigue properties of laboratory specimens of the alloys developed since 1948 are shown in Table VI; these data cannot be applied directly in design. A specimen of alloy ZK60A-T5 (static yield strength 42,000 psi) with a machined 60° notch of 0.001-in. radius has a fatigue limit of 4000 psi at 500 million cycles, compared with 16,000 psi for the unnotched specimen. This is a notch factor of 0.25 (4000/16,000). For a shorter life of 100,000 cycles, the notch factor is about 0.48. As the severity of the notch decreases, its effect on the fatigue limit decreases rapidly. For instance, a semicircular notch of 0.047-in. radius reduces fatigue strength only 20% compared with 75% reduction caused by the sharp V-notch cited above.

When fatigue is the controlling factor in design, every effort should be made to decrease the severity of the stress raisers. The use of generous fillets in re-entrant corners and gradual, rather than abrupt, changes of section contribute greatly in increasing the resistance to fatigue failure. Situations which lead to the overlapping effects of one stress raiser on another

should be eliminated. Further improvement in fatigue strength can be obtained by some operation that will leave the part with a stress pattern conducive to long life. Cold working the surface of a critical region by rolling or peening to achieve appreciable plastic deformation produces a residual compressive stress on the surface and leads to an increase in fatigue life.

Surface rolling of radii is especially beneficial to the fatigue resistance of a part, as the radius is generally the location of higher-than-nominal stresses. In surface rolling, the size and shape of the roller, as well as the feed and pressure, are controlled, to obtain a definite plastic deformation of the surface layers for an appreciable depth (0.010 to 0.015 in.); control is also necessary in shot peening. In all surface working processes, caution is necessary to avoid surface cracks, which decrease fatigue life.

These and other surface working processes are discussed in detail on page 104.

Applications at Elevated Temperatures. Two types of magnesium alloys are being used at elevated temperatures: (1) Mg-Al-Zn, comprising alloys AZ63A, AZ91C and AZ92A and (2) Mg-RE-Zr, with or without Zn, comprising EK30A, EK41A and EZ33A. (RE signifies rare earths.)

The Mg-Al-Zn alloys are stable to about 200 F and often provide satisfactory service in stressed parts up to 400 F. Elevated temperature properties are given for these alloys in the 1948 Handbook, page 1003. Beginning between 200 and 400 F, a lighter structure can be made with EK30A, EK41A or EZ33A, providing the designed wall thickness is at least as great as the minimum that is castable, which is about $\frac{1}{8}$ in.

Slight differences in short-time tensile properties can be found among the rare-earth-metal alloys; however, if long-time properties at elevated temperature are the only important con-

Table VII. Typical Short-Time Elevated Temperature Tensile Properties of Mg-RE-Zr and Mg-RE-Zn-Zr Alloys

Temp, deg Fahr	Tensile Strength, psi	Yield Strength, psi	% Elong in 2 in.
Alloy EK30A-T5 ^(a)			
70	23,000	16,000	2
300	21,000	15,000	8
400	20,000	14,000	13
500	18,000	12,000	30
600	12,000	8,000	70
Alloy EK41A-T5 ^(b)			
70	22,000	17,000	1
400	20,000	13,000	14
500	18,000	12,000	31
600	12,000	8,000	54
Alloy EZ33A-T5 ^(c)			
70	26,000	20,000	4
300	23,000	19,000	10
400	22,000	17,000	12
500	20,000	15,000	19
600	14,000	9,000	53

(a) 16 hr at 1050 F, air cool; 16 hr at 400 F. (b) 16 hr at 400 F. (c) 5 hr at 420 F

Table VI. Fatigue Properties of Five Magnesium Alloys

Alloy	Stress at Indicated Cycles, psi			
	10 ³	10 ⁴	10 ⁵	10 ⁶
ZK60-T5 Extruded	29,000	24,000	20,000	19,000
ZK51-T5				
ZK51-T6 Cast	18,000	14,000	11,000	10,000
EK30-T6 EK41-T5				
EK41-T6 EZ33-T3 Cast	15,000	12,000	9,000	8,000

R. R. Moore rotating-beam fatigue testing machine with unnotched specimens

sideration, cost will govern selection because the creep properties of the various alloys are comparable and service performance of all is similar.

Table VII shows the short-time tensile properties at elevated temperatures, for the alloys containing rare earth metals; Table VIII shows the effect of duration of creep testing on total extension. As there is no significant difference in creep properties among the three rare-earth-metal alloys, the properties for all are averaged in Table VIII. For 0.5% total extension in 1000 hr at 400°F, the table shows a creep stress of 7000 psi; the corresponding stress for the Mg-Al-Zn alloy is 1700 psi.

Protection of Assemblies

Magnesium in contact with magnesium or other metals must be protected against corrosion. The protective measures discussed here apply to the most severe service, such as continuous weathering and exposure to intermittent wetting with chloride-laden splash. For interior use where condensation is unlikely, normal paint coatings usually provide ample protection against bimetallic couples.

Magnesium-to-Magnesium Contacts. Galvanic corrosion between various magnesium alloys is negligible, but faying surfaces should have at least one coat of a chromate-pigmented primer.

Magnesium-to-Wood Contacts. Wood will hold water in contact with magnesium for a long period, and the natural acids of the wood also are corro-

Table VIII. Typical Creep Properties of Cast Magnesium Alloys Containing Rare Earth Metals

Temperature, deg Fahr	Hours Under Load	Tensile Stress Resulting in Indicated Total Extension, psi			
		0.1%	0.2%	0.5%	1%
400	1.....	6,000	10,000	13,000	15,000
	10.....	6,000	9,000	12,000	13,000
	100.....	5,000	8,000	10,000	11,000
	1000.....	4,000	6,000	7,000	8,000
500	1.....	5,000	8,000	10,000	12,000
	10.....	4,000	5,000	7,000	8,000
	100.....	2,000	3,000	4,000	5,000
	1000.....	2,000	2,000	2,000	3,000
600	1.....	2,000	3,000	4,000	5,000
	10.....	2,000	2,000	3,000	3,000
	100.....	2,000	1,000	2,000	2,000
	1000.....	1,000	1,000	1,000	1,000

Tests made on separately cast specimens. Total extension includes initial extension after test load was applied, as well as deformation by creep. Properties for all three alloys averaged; there is no significant difference among them. Six samples of each alloy were tested for 1000 hr.

two or three finish coats). Additional finish coats may then be applied after assembly for decorative purposes.

Most sealing compounds are satisfactory for use with magnesium; many contain chromates as corrosion inhibitors. Bitumastic materials should be avoided because they may bleed through paint. Any excess of sealing compound should be squeezed out during assembly and filleted or beaded to protect the edges.

Tapes are of organic rubber or plastic, or contain cloth to support a sealing compound. The rubber or plastic tapes form a positive insulating barrier, but the tape must extend out past the edges of the joint far enough so water or mud cannot bridge the tape and complete the galvanic circuit.

Gaskets and Shim Materials should be tested under service conditions. In highly stressed joints, or in joints that might cut or pound out rubber or fabric insulating materials, the required gasket may be of 52S or 61S aluminum sheet. All gaskets must extend beyond the joint far enough to prevent bridging by solution or mud. Shims should be primed with zinc chromate primer, as should the magnesium, and the joint can be treated as a magnesium-magnesium contact. Hygroscopic gasket materials or those containing salts that corrode magnesium should not be used.

Rivets, Bolts, and Inserts. Magnesium alloys are not suitable for fasteners; aluminum alloy 56S rivets are recommended. (Rivets of 53S are almost as compatible with magnesium as 56S but are weaker.) Aluminum rivets should be anodized or chemically treated before use. Bolts and hardware should be of 61S aluminum alloy. Under cadmium plated steel bolts, 52S aluminum washers should be used.

Steel and copper rivets and steel, Monel, nickel, brass and aluminum (other than 56S or 53S) bolts and screws should not be used bare in magnesium assemblies because there is no easy way to insulate them from the magnesium. Zinc or cadmium plating on such parts is recommended, chemically treated to activate the electrolyte for better paint adhesion.

Inserts used in magnesium should be cadmium or zinc plated. If service conditions are severe, an annular groove at least $\frac{1}{8}$ in. wide should be filled with caulking compound. Inserts that are covered with grease or oil during service need no special protection.

Cathodic Protection

A metallic structure may be protected against corrosion by being made the cathode of a direct-current electrical system. The current may be supplied from an external source (a battery or direct current); another system utilizes sacrificial or corroding galvanic anodes such as magnesium to supply the potential difference.

To serve as a galvanic anode a metal obviously must be anodic to the metal to be protected under the particular operating conditions; it should not be susceptible to excessive polarization; and it should deliver the maximum ampere-hours per pound. An important practical factor is the "efficiency" of the anode. One pound of pure magnesium should theoretically yield 997 amp-hr; in practice it comes to about 500 amp-hr.

Magnesium alloy galvanic anodes are usually supplied as castings or extruded rod with a core of steel rod or wire to maintain good electrical connection. Magnesium alloys containing aluminum and zinc are the most widely used. For extruded anodes AZ31B alloy is preferred; the specified maxi-

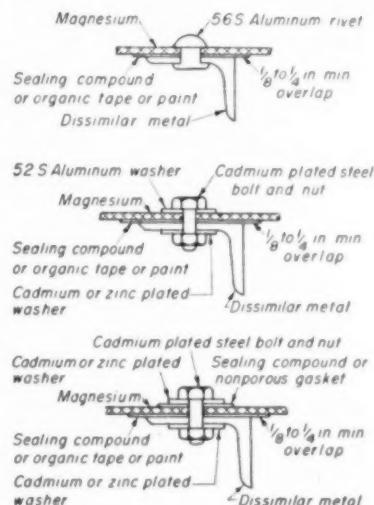


Fig. 3. Alternative Methods of Riveting and Bolting Magnesium to Dissimilar Metal or Wood

Table IX. Preferred Metals for Bimetallic Joints in Order of Preference

Magnesium to Aluminum	Magnesium to Steel
1 56S (wire & rivets)	1 Zinc plated steel
2 61S (extrusions & sheet)	2 Zinc dipped steel
3 52S (sheet)	3 Cadmium plated steel
4 53S (extrusions & rivets)	

sive. Wood should be sealed with paint or varnish, and the faying surface of the magnesium should be treated with a chromate primer.

Magnesium-to-Dissimilar Metals. To prevent galvanic attack between magnesium and dissimilar metals, the dissimilar metal should be chosen for best compatibility (Table IX) and the joint should be insulated by a nonconductive sealing compound, tape or paint, as indicated in Fig. 3. These barrier materials must remain nonconductive during use.

Paints, Sealing Compounds and Tapes. The effectiveness of a paint as an insulating barrier is directly related to its water permeability; if water soaks through, the circuit is completed and galvanic attack begins. Primers of the zinc chromate pigmented type are satisfactory only in mildly corrosive environments. Some primers and most finish coats resist water penetration and are recommended for use in more corrosive environments. Wherever paints are used, both dissimilar metal faying surfaces should receive the entire paint system before assembly (two or three coats of primer or one primer plus one,

mum contents of iron, nickel and copper in this high-purity alloy should not be exceeded. For cast anodes, some modification of alloy AZ63A is generally preferred; 0.003% max Fe and 0.002% max Ni, markedly improve the efficiency and life of this type of anode; copper is specified as 0.05% max in some variations. Commercially pure magnesium (99.8%, ASTM B92-52) is sometimes used.

Magnesium galvanic anodes serve principally for the cathodic protection of ferrous structures, often in conjunction with organic coatings. Underground, magnesium anodes are used to protect the outside surface of gas, oil and water pipe lines and electrical grounding systems. A mixture of chemical compounds, called "backfill", often is put around the buried anodes to reduce their resistance to ground, particularly in soils of high resistivity. The backfill generally contains electrolytes such as gypsum and sodium sulfate and an inert water-retaining ingredient such as bentonite. Even with

backfills, buried magnesium anodes are sometimes limited to soils with resistivity less than 5000 ohm-cm. Such soils also may require more anodes or longer anodes.

Underground anodes are usually cylindrical, square or D-shaped castings, the latter typically 4 by 4 by 17 to 20 in. and weighing 16 to 20 lb. In soils of higher resistivity, extruded rod anodes ("ribbon anodes" about $\frac{1}{8}$ in. in cross section) may be used, so as to expose a larger area of anode and reduce resistance to ground by burying long lengths of the extruded rod parallel to pipe lines.

Magnesium anodes can protect galvanized steel tanks in the majority of water supply systems, augmenting the protection afforded by the zinc on the steel. Anodes for this service are usually supplied as cast or extruded rods with diameters corresponding to standard pipe sizes, for convenience in supporting them from threaded apertures in the tank.

To protect pipe lines, piers, ship

hulls, ballast tanks and other equipment from sea water, anodes are usually castings of the same size or larger than those used for buried pipe. With uncoated steel structures such as piers and pilings, a high initial current is sometimes applied for a short time to form a uniform, hard, calcareous coating on the anode. This coating reduces the subsequent current required for adequate protection. To provide this initial high current, supplementary ribbon anodes are practical.

Magnesium anodes can also be employed for the protection of nonferrous metals that are cathodic under the operating conditions. In structures involving amphoteric metals such as lead and aluminum alloys, if the amphoteric metals are polarized to extremely high potentials, they may corrode cathodically because of an alkaline environment formed at their surface. The anode installation should, therefore, be carefully controlled so as to provide only enough current to protect the amphoteric metals.

PROPERTIES OF MAGNESIUM ALLOYS

Mg - 5.7 Zn - 0.55 Zr

- A 3** *ASTM number.* ZK60A, B107-53T (bars, rods and shapes), B217-53T (tubing)
- 4** *Government number.* Alloy ZK60A, MIL-M-5354 (extrusions)
- 5** *Other designations.* AMS 4352 (extrusions), AMS 4362 (forgings)
- B 1** *Typical uses.* Highest strength of magnesium wrought alloys combined with good ductility. Available as extruded products and press forgings. Heat treated for maximum strength.
- C 1** *Density at 20°C (68°F).* 1.83 g per cu cm (0.066 lb per cu in.)
- D 1** *Liquidus temperature.* 635°C (1175°F)
- 2** *Solidus temperature.* 520°C (968°F)
- 3** *Minimum "burning" (liquation) temperature.* 340°C (645°F), approx
- 6** *Thermal expansion at 40°C (104°F).* 0.000026 per °C
- 11** *Specific heat at 25°C (78°F).* 0.25 cal per g
- 13** *Latent heat of fusion.* 89 cal per g
- 16** *Thermal conductivity at 20°C (68°F).* 0.28 cal/sq cm/cm/C/sec, condition F; 0.29 cal/sq cm/cm/C/sec, condition T5

- E 1** *Volume conductivity referred to standard copper.* 29%, condition F; 30%, condition T5
- 2** *Electrical resistivity at 20°C (68°F).* 6.0 microhm-cm, condition F; 5.7 microhm-cm, condition T5
- K** *Mechanical properties.* See Table I.
- All forms.** Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
- 4** *Machinability index* (free-cutting brass = 100). 500
- L** *Radiography.* See page 1013, 1948 Metals Handbook.
- M** *Composition limits. Components:* 4.8 to 6.2% Zn, 0.45% min Zr; *impurities:* 0.3% max other elements (total)
- N 1** *Melting temperature.* 520 to 635°C (968 to 1175°F)
- 2** *Casting temperature (ingot).* 690 to 746°C (1275 to 1375°F)
- 3** *Alloying.* Add zinc as zinc; add zirconium as magnesium-zirconium alloy or as zirconium-containing salt.
- 7** *Hot working temperature.* 316 to 399°C (600 to 750°F)
- 8** *Shortness temperature.* 316°C (600°F), cast; 510°C (950°F), wrought
- 15** *Heat treatment.* Aging, 150°C (300°F) for 24 hr in air; then cool in air.
- 17** *Joining. Rivet composition.* Aluminum alloy 56S-H12. *Inert-gas-shielded arc welding* is in limited use.

Table I. Typical Mechanical Properties of Alloy ZK60A at Room Temperature

Condition	Tensile Strength, psi	Tensile Yield Strength, ^(a) psi	Elongation, %	Brinell Hardness Number ^(b)	Rockwell Hardness	Shear Strength, psi	Compressive Yield Strength, ^(c) psi	Bearing Strength, psi	Bearing Yield Strength, ^(d) psi
Bars, Rods and Shapes									
F	49,000	38,000	14	75	E 84	25,000	33,000	80,000	57,000
T5	53,000	44,000	11	82	E 88	26,000	36,000	83,000	60,000
Hollow Shapes and Tubing									
F	46,000	34,000	12	.....	E 84	.....	25,000	.....	.....
T5	50,000	40,000	11	82	E 88	.....	29,000	.....	.....

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 2% of hole diameter offset, 2½-diam edge distance

Mg - 4.5 Zn - 0.7 Zr

- A 3** *ASTM number.* ZK51A, B80-53T (sand cast)
- B 1** *Typical uses.* Sand castings of high yield strength with low microporosity, uniformity of properties throughout large complex castings and requiring only low-temperature heat treatment
- C 1** *Density at 20°C (68°F).* 1.8 g per cu cm (0.065 lb per cu in.)

- D 1** *Liquidus temperature.* 635°C (1175°F)
- 2** *Solidus temperature.* 560°C (1040°F)
- 6** *Thermal expansion 20 to 200°C (68 to 392°F).* 0.000027 per °C
- 11** *Specific heat 20 to 100°C (68 to 212°F).* 0.23 cal per g
- 16** *Thermal conductivity at 20°C (68°F).* 0.27 cal/sq cm/cm/C/sec

Mg - 4.5 Zn - 0.7 Zr (Cont.)

E 2 Electrical resistivity at 20°C (68°F). 6.7 microhm-cm.

K 1 Mechanical properties.

Condition	Tensile Strength, psi	Tensile Yield Strength, ^(a) psi	Elongation, %	Brinell Hardness Number (b)
As cast	33,000	19,000	11	60
Heat treated ^(c)	40,000	23,500	8	70

(a) 0.2% offset. Compressive yield strength (0.2% offset) is approximately the same as tensile yield strength. (b) 500-kg load, 10-mm ball. (c) 12 hr at 180°C (355°F).

All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35

L 2 Radiography. See page 1013, 1948 Metals Handbook.
M 1 Composition limits. Components: 3.6 to 5.5% Zn, 0.50% min Zr; impurities: 0.10% max Cu, 0.01% max Ni, 0.3% max others (total)

- N 1 Melting temperature.** 560 to 635°C (1040 to 1175°F)
2 Casting temperature. 750 to 820°C (1380 to 1490°F)
3 Alloying. Add zinc as pure zinc; add zirconium as zirconium-containing salt or as magnesium-zirconium master alloy.
5 Type of flux. Magnesium melting flux
6 Precautions in melting. See page 1013, 1948 Metals Handbook. Avoid contamination with aluminum.
15 Heat treatment. 12 hr at 180°C (355°F)
17 Joining. Rivet composition. Aluminum alloy 56S-H12. Inert-gas-shielded arc welding is difficult.

Mg - 3.4 Rare Earth - 0.4 Zr

A 3 ASTM number. EK30A, B80-53T (sand cast)

B 1 Typical uses. Applications requiring good creep properties at 300 to 500°F

C 1 Density at 20°C (68°F). 1.79 g per cu cm (0.065 lb per cu in.)

D 2 Solidus temperature. 593°C (1100°F)

6 Thermal expansion at 40°C (104°F). 0.000026 per °C

11 Specific heat at 25°C (76°F). 0.25 cal per g

13 Latent heat of fusion. 89 cal per g

16 Thermal conductivity at 20°C (68°F).

0.25 cal/sq cm/cm/°C/sec, approx

E 1 Volume conductivity referred to standard copper (condition T6). 25%

2 Electrical resistivity at 20°C (68°F) (condition T6). 6.9 microhm-cm

K 1 Mechanical properties (condition T6). Tensile strength 23,000 psi; yield strength 16,000 psi; elongation 3%; Brinell hardness number 45; Rockwell E 49; compressive yield strength (0.2% offset) 16,000 psi; modulus of elasticity 6,500,000 psi; modulus of rigidity 2,400,000 psi; Poisson's ratio 0.35

L 2 Radiography. See page 1013, 1948 Metals Handbook.

M 1 Composition limits. Components: 2.5 to 4% rare earths, 0.2% min Zr; impurities: 0.10% max Cu, 0.01% max Ni, 0.3% max Zn, 0.3% max other elements (total)

N 2 Casting temperature (sand). 649 to 843°C (1200 to 1550°F)

3 Alloying. Add rare earth as mischmetal or as a magnesium-rare earth hardener; add zirconium as magnesium-zirconium master alloy or as zirconium-containing salt.

5 Type of flux. Free from MgCl₂

6 Precautions in melting. Avoid contamination with aluminum; use enough flux to avoid preferential oxidation of rare earth metals.

15 Heat treatment.

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution	570	1060 max	18	Air
Aging	205	400	16	Air

17 Joining. Rivet composition. Aluminum alloy 56S-H12. Inert-gas-shielded arc welding with filler rod of same composition as base metal

Mg - 4.0 Rare Earth - 0.7 Zr

A 3 ASTM number. EK41A, B80-53T (sand cast)

B 1 Typical uses. Applications requiring good creep properties at 300 to 500°F

C 1 Density at 20°C (68°F). 1.81 g per cu cm (0.066 lb per cu in.)

D 2 Solidus temperature. 591°C (1095°F)

6 Thermal expansion at 40°C (104°F). 0.000026 per °C

11 Specific heat at 25°C (78°F). 0.25 cal per g

13 Latent heat of fusion. 89 cal per g

16 Thermal conductivity at 20°C (68°F).

0.25 cal/sq cm/cm/°C/sec, condition T5;

0.23 cal/sq cm/cm/°C/sec, condition T6

E 1 Volume conductivity referred to standard copper. 24%, condition T5; 26%, condition T6

2 Electrical resistivity at 20°C (68°F). 6.6 microhm-cm, condition T5; 7.3 microhm-cm, condition T6

K 1 Mechanical properties.

Condition	Tensile Strength, psi	Tensile Yield Strength, ^(a) psi	Elongation, %	Hardness Rockwell
Aged (T5)	23,000	16,000	1	E 49
Solution treated and aged (T6)	25,000	18,000	2	E 59

(a) 0.2% offset. Compressive yield strength (0.2% offset) is approximately the same as tensile yield strength. (b) 500-kg load, 10-mm ball

L 2 Radiography. See page 1013, 1948 Metals Handbook.

M 1 Composition limits. Components: 3.0 to 5.0% rare earths, 0.4 to 1.0% Zr; impurities: 0.10% max Cu, 0.01% max Ni, 0.3% max Zn, 0.3% max other impurities (total)

N 2 Casting temperature. 649 to 843°C (1200 to 1550°F)

3 Alloying. Add rare earths as mischmetal or magnesium-rare earth hardener, zirconium as magnesium-zirconium alloy or as a zirconium-containing salt.

5 Type of flux. Free from MgCl₂

6 Precautions in melting. See page 1014, 1948 Metals Handbook. Avoid contamination with aluminum; use enough flux to avoid preferential oxidation of rare earth metals.

15 Heat treatment.

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution	570 max	1060 max	18	Air
Aging	205	400	16	Air

17 Joining. Rivet composition. Aluminum alloy 56S-H12. Inert-gas-shielded arc welding with filler rod of same composition as base metal

Mg - 3.0 Rare Earth - 2.5 Zn - 0.6 Zr

- A 3 ASTM number.** EZ33A, B80-53T (sand cast)
- 4 Government number.** EZ33A, MIL-M-9433 (USAF)
- B 1 Typical uses.** Pressure-tight sand castings free from microporosity, with good combination of tensile strength, yield strength and elongation, both at room temperature and elevated temperatures
- C 1 Density at 20°C (68°F).** 1.83 g per cu cm (0.066 lb per cu in.)
- D 1 Liquidus temperature.** 637°C (1178°F)
- 2 Solidus temperature.** 556°C (1033°F)
- 6 Thermal expansion** 20 to 100°C (68 to 212°F). 0.0000268 per °C
- 11 Specific heat at 20°C (68°F).** 0.25 cal per g
- 13 Latent heat of fusion.** 89 cal per g
- 16 Thermal conductivity at 20°C (68°F).** 0.24 cal/sq cm cm/°C sec
- E 2 Electrical resistivity at 20°C (68°F).** 7.1 microhm-cm
- K 1 Mechanical properties (aged).** Tensile strength 23,000 psi; 0.2% yield strength 14,500 psi; elongation 3%; Brinell hardness number 54; 0.2% compressive yield

- strength 14,500 psi; modulus of elasticity 6,500,000 psi; modulus of rigidity 2,500,000 psi; Poisson's ratio 0.3
- L 2 Radiography.** See page 1013, 1948 Metals Handbook.
- M 1 Composition limits.** Components: 2.5 to 4.0% rare earths, 2.0 to 4.0% Zn, 0.50% min Zr; impurities: 0.10% max Cu, 0.01% max Ni, 0.3% max total other
- N 1 Melting temperature.** 556 to 637°C (1033 to 1178°F)
- 2 Casting temperature.** 750 to 830°C (1380 to 1525°F)
- 3 Alloying.** Add rare earths as mischmetal or magnesium - rare earth hardener, zinc as pure zinc, zirconium as zirconium-containing salt or magnesium-zirconium master alloy.
- 5 Type of flux.** Free from MgCl₂
- 6 Precautions in melting.** See page 1014, 1948 Handbook. Avoid contamination with aluminum; use sufficient flux to avoid preferential oxidation of rare earth metals.
- 15 Heat treatment.** Aging, 420°F for 5 hr
- 17 Joining. Rivet composition.** Aluminum alloy 56S-H12. Inert-gas-shielded arc welding is used with filler rod of same composition as base metal.

Mg - 8.6 Al - 0.7 Zn - 0.15 Mn

- A 3 ASTM number.** AZ91C, B80-51T (sand cast) and B93-52T (ingot)
- 4 Government number.** AZ91C, QQ-M-56
- B 1 Typical uses.** General sand casting alloy having good strength, pressure tightness and ductility
- C 1 Density at 20°C (68°F).** 1.81 g per cu cm (0.066 lb per cu in.)
- D 1 Liquidus temperature.** 596°C (1105°F)
- 2 Solidus temperature.** 468°C (875°F)
- 3 Minimum "burning" (liquation) temperature.** 420°C (790°F)
- 6 Thermal expansion at 40°C (104°F).** 0.000026 per °C
- 11 Specific heat at 25°C (78°F).** 0.25 cal per g
- 13 Latent heat of fusion.** 89 cal per g
- 16 Thermal conductivity** 100 to 300°C (212 to 572°F). 0.17 cal/sq cm cm/°C sec
- E 1 Volume conductivity referred to standard copper.** 10.2%
- 2 Electrical resistivity at 20°C (68°F).** 17.0 microhm-cm
- K 1 Mechanical properties.** See Table I.
- All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35
- 4 Machinability index** (free-cutting brass = 100). 500

- L 2 Radiography.** See page 1013, 1948 Metals Handbook.
- M 1 Composition limits.** Components: 8.1 to 9.3% Al, 0.4 to 1.0% Zn, 0.13% min Mn; impurities: 0.3% max Si, 0.10% max Cu, 0.01% max Ni, 0.3% max other elements (total)
- 2 Consequences of exceeding impurity limits.** Resistance to corrosion decreases with increasing copper and nickel content. More than 0.50% Si increases brittleness.
- N 1 Melting temperature.** 468 to 596°C (875 to 1105°F)
- 2 Casting temperature.** 732 to 843°C (1350 to 1550°F)
- 3 Alloying.** Add aluminum as aluminum or Al-Mn alloy; add zinc as zinc; add manganese as 95 Al - 5 Mn.
- 5 Type of flux.** Magnesium melting flux
- 6 Precautions in melting.** See page 1013, 1948 Metals Handbook.
- 15 Heat treatment.**

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution	415 max	780 max	18	air
Aging	168	335	18	air

- 17 Joining. Rivet composition.** Aluminum alloy 56S-H12. Inert-gas-shielded arc welding is common using filler metal of same composition or alloy AZ92A.

Table I. Typical Mechanical Properties of AZ91C at Room Temperature

Condition	Tensile Strength, psi	Tensile Yield Strength, ^(a) psi	Elongation, %	Brinell Hardness Number ^(b)	Rockwell Hardness	Shear Strength, psi	Compressive Strength, ^(c) psi	Bearing Strength, psi	Bearing Yield Strength, ^(c) psi
F	24,000	14,000	2	52	E 62	18,000	14,000	50,000	30,000
T4	40,000	14,000	11	55	E 66	18,600	14,000	50,000	36,000
T6	40,000	19,000	4	73	E 83	21,000	19,000	65,000	45,000

^(a) At 0.2% offset. ^(b) 500-kg load, 10-mm ball. ^(c) 2% of hole diameter offset; 2^{1/2}-diam edge distance

Properties of Magnesium and Magnesium Alloys

AN INDEX TO THE PROPERTY DATA IN THE 1948 METALS HANDBOOK

Magnesium (99.80 Mg)	1013	Mg - 1.25 Al - 1 Mn (die castings)	1019
Mg - 4 Al - 0.2 Mn (sand castings)	1014	Mg - 1.5 Mn (cast and wrought)	1020
Mg - 8 Al - 0.2 Mn (sand castings)	1015	Mg - 3 Al - 1 Zn - 0.3 Mn (wrought)	1021
Mg - 10 Al - 0.1 Mn (cast and wrought)	1015	Mg - 5 Al - 1 Zn - 0.25 Mn (sheet)	1022
Mg - 6 Al - 3 Zn - 0.2 Mn (sand castings)	1017	Mg - 6 Al - 1 Zn - 0.2 Mn (wrought)	1022
Mg - 9 Al - 2 Zn - 0.1 Mn (castings)	1018	Mg - 8.5 Al - 0.5 Zn - 0.15 Mn (wrought)	1023
Mg - 9 Al - 0.7 Zn - 0.2 Mn (die castings)	1019	Mg - 5 Sn - 3 Al - 0.5 Mn (forgings)	1024

Titanium and Titanium Alloys

By the ASM Committee on Titanium

COMMERCIAL production of titanium has risen steadily from 3 tons in 1948 to 2250 tons in 1953. Plans for rapid expansion indicate a producing capacity greater than 20,000 tons by 1956. Titanium-bearing ores, particularly ilmenite, are readily available but the technical difficulties in recovering, melting and processing the metal are severe. These make titanium costly; however, the desirable strength-weight ratio in the temperature range from 300 to 700 F has justified use of the metal in airframes and aircraft engines, even at prices 30 to 40 times as great as for stainless steel.

All commercial titanium is now produced by the Kroll process—magnesium reduction of titanium tetrachloride. The titanium is recovered from the reaction mixture as a spongy mass which, after crushing and sizing, forms the basic material for production of ingots. Rolling ingots to rod, sheet and other shapes requires equipment similar to that used for steel.

General information on the chemistry, economic position, political status and bibliography of titanium is available, respectively, in the following recent references:

Jelks Barksdale, "Titanium", Ronald Press, New York, 1949, 590 pages
"Titanium Metal and Its Future", Hen-

"*Titanium Metal and Its Future*", Harvard Business School, Cambridge, Mass., 1952, 103 pages

The Technology of Titanium, ch 13, vol II and ch 6, vol IV, "Resources for Freedom", The President's Materials Policy Commission, Supt of Documents, Washington, June 1952

Battelle Memorial Inst. "Titanium Bibliography, 1900 to 1951", PB 111,196, and 1952 Supplement, PB 111,196-S, U. S. Dept of Commerce, Office of Technical Services, Washington.

Progress in both the processing and physical metallurgy of titanium is being made at a rapid rate. Current metallurgical literature should be consulted to supplement the more basic information given in the sections of this article which follow.

Production of Ingots

Molten titanium reacts with oxygen and nitrogen in air. In small fractions of 1%, these act as hardening additions and in amounts over 0.5% O₂ or 0.25% N₂ they reduce ductility drastically. Hydrogen is also an embrittling agent in titanium. Therefore, adequate protection must be provided against air and moisture in melting furnaces by vacuum technology or inert atmospheres of pure argon or helium.

Molten titanium also reacts vigorously with or dissolves the refractories or metals which might be considered to contain it at its melting temperature of slightly over 3000 F. Carbon is dissolved on short contact in amounts up to 1.0% and forms generally detriment-

This is a new subject for
the ASM Metals Handbook

Subdivision	Page
Production of Ingots	80
Production of Mill Forms	80
Forging	80
Forming of Sheet	81
Machining and Grinding	82
Welding	82
Heat Treating	83
Cleaning and Finishing	83
Corrosion Resistance	83
Metallography	84
Applications	85
Design	85
Selection of Alloys	86
 Properties	
Titanium (99.9 Ti)	87
Titanium (99.2 Ti)	88
Titanium (99.0 Ti)	88
Titanium Alloys	89

tal carbide inclusions in the solid metal. Oxygen contamination results from contact with oxide or silicate refractories. Therefore, the usual methods of melting and casting are ruled out, and commercial practice has generally adopted the principle of von Bolten of arc-melting in inert atmosphere at near-atmospheric or greatly reduced pressure in a water-cooled metal container, usually of copper.

Electrodes of tungsten or carbon, or consumable electrodes of titanium are used. Carbon or tungsten electrodes are subject to spalling and melting particularly if spattered with titanium. Remelting with a consumable electrode is used in some practices to improve chemical homogeneity and decrease voids or inclusions. Some mill and customer scrap is being remelted in ingot production.

Design and engineering problems have largely been overcome for the above operations; cylindrical titanium alloy ingots weighing up to 2 tons are now being produced commercially. Small castings have been made experimentally but not commercially.

Production of Mill Forms

Titanium ingots are cylindrical. Hot working temperatures are much lower than for steel; finishing temperatures must be more carefully controlled. Working pressures are greater because of the lower temperatures; lighter drafts are taken; and surfaces are protected more carefully because scoring and scratches are more likely to persist and mar the final finish.

Alpha-beta titanium alloys are subject to excessive grain growth if heated into the single-phase beta region and transformation hardening and embrittlement are likely if cooling from this region is not controlled properly. Hence, the alloys are usually worked in the alpha-beta temperature range. Hot rolling temperatures are 100 to 200°F below those recommended for

forging (see next section), and finishing temperatures are between 1500 and 1200 F, depending on the alloy. Rolling is followed by stabilizing at 1100 to 1300 F. All-alpha alloys are forged by starting in the all-beta region and finishing in the all-alpha region. Hot rolling is done in the all-alpha region at temperatures 200 to 300 F higher than those used for alpha-beta alloys.

Titanium and titanium alloys are not free-scaling under usual conditions of heating, and oxygen from the scale dissolves readily in the underlying metal. Excessive oxidation, which hardens and embrittles the surface, is avoided by working the metal at the lowest feasible temperatures and using short heating times. In this respect, temperature is more important than atmosphere control, and oxidizing, neutral and reducing atmospheres are all used. However, an oxidizing atmosphere is recommended to minimize hydrogen contamination when possible embrittlement is a factor. Surfaces are carefully conditioned at frequent intervals during rolling.

Tubes and other shapes have been hot extruded experimentally using glass lubricants. Also, molybdenum sulfide and graphite lubricants have been used in experimental extrusion of titanium. In the cold drawing of tubes, simple shapes and wire, oxidized surfaces (including anodized) and electroplated coatings have been utilized in conjunction with heavy lubricants; such coatings should be removed carefully before annealing, to prevent surface contamination. Cold drawing and rolling require frequent intermediate anneals at 1100 to 1500 F. All-alpha alloys like Ti-5 Al-2.5 Sn are annealed at 1500 F; aluminum-free alpha-beta alloys, at 1100 F; and unalloyed titanium at 1300 F. Vacuum annealing has been used successfully for wire and tubing to minimize surface contamination.

Forging

To produce the same amount of metal flow in forging, about 30% more power is required for titanium than for alloy steel. In making some small forgings such as compressor blades, hammers of 60% higher rating may be needed.

Because titanium does not fill die contours so readily as alloy steel, stainless steel or aluminum, the impression dies for forging titanium must have larger radii and fillets. For intricate drop forgings, more die stages are usually needed for titanium than for steel

any needed for titanium than for steel. Shrinkage allowance in die sinking is 0.100 in. per ft, compared with 0.187 for dies to forge steel. The working surfaces of the die should be well polished to facilitate the flow of metal; graphite and oil lubricants may prove helpful also.

Titanium forging stock must be free from surface and internal defects; billets should be rough machined; bar stock, turned or centerless ground. During heating for forging, the surface should be protected by a furnace atmosphere that is neutral or only slightly oxidizing; the furnace hearth should be kept free from loose scale; and direct impingement of the flame on the work should be avoided. Muffle-type gas-fired furnaces or electric furnaces are recommended.

Most large finished forgings are sta-

bilized by annealing at 1100 to 1300 F for periods up to 24 hr and then cooling in air. Cracks or seams should be removed by grinding the metal while it is warm (up to about 900 F), and the forging should be stress relieved immediately thereafter.

The following heating practices have given satisfactory results:

Unalloyed Titanium. Forging range should be from 1600 to 1750 F with a finishing temperature of 1450 F. Billets over 6 in. thick should be preheated at 1400 F to minimize scaling in the high-temperature furnace. A heating rate of 15 min per in. of section is satisfactory.

Alpha-Beta Alloys. The forging range extends to 1850 F. Billets less than 8 in. thick for upset forgings should not be forged above 1650 F; larger sections can be forged up to 1750 F. Finishing temperatures should be between 1500 and 1400 F. The alloy with 4 to 5% Al should be forged from 1850 and finished between 1600 and 1500 F. Reductions of 50% or more per furnace heating are common for the alpha-beta alloy without aluminum; the alloy containing aluminum is more difficult to work at any temperature but it can be forged satisfactorily at higher temperatures.

All-Alpha Alloy. The better oxidation resistance of the all-alpha alloy permits the use of higher forging temperatures; 2000 to 2100 F is the normal top. At these higher temperatures, less power is needed to forge this alloy than is required for the alpha-beta alloys at the lower temperatures normal for those alloys.

Cleaning. Titanium forgings should be pickled, or cleaned by abrasion (see page 83). Otherwise, machining is more difficult and a decreased fatigue life results from the hard brittle skin.

Forming of Sheet

The formability of titanium is influenced principally by: (1) high yield strength, (2) low ductility at room temperature, (3) sensitivity to rate of strain, (4) directional effects (anisotropy), (5) low ratio of uniform strain to necking strain (about half that of annealed stainless steel), and (6) notch sensitivity.

In forming, annealed unalloyed titanium behaves about like $\frac{1}{4}$ -hard 18-8 stainless steel; the presently available titanium alloys, in the annealed condition, are similar to $\frac{1}{2}$ -hard 18-8. Only with great difficulty can work hardened titanium be formed by conventional methods. The use of suitable alloys rather than work hardened grades is suggested, for maximum formability at a given strength level.

General Considerations. Titanium is sensitive to rates of forming, and slow rates are preferred for maximum formability. The springback resulting from forming unalloyed titanium (70,000 psi yield strength) is approximately equal to that for $\frac{1}{4}$ -hard 18-8. In alloy titanium the springback is about 25% greater than with $\frac{1}{2}$ -hard 18-8.

Hot forming is used in producing smaller bend radii, increased elongation and less springback. Any degree of heating is beneficial; the blanks are commonly heated to between 500 and 600 F. for unalloyed titanium, or 800 to 1000 F. for titanium alloys. Higher temperatures, within the ranges mentioned, are preferred for the more difficult forming jobs, but uniformity of heat-

ing is as important as a particular temperature level. Such heating of alloys should not be prolonged unnecessarily because of danger of surface contamination by oxygen. Use hand torches cautiously because of the difficulty of maintaining uniform temperatures and the danger of overheating and consequent embrittlement. Where feasible, heated dies are desirable to avoid chilling of the hot blanks, particularly with thin sheet.

Formed titanium parts, especially alloy parts, may crack from residual stresses. Stress relieving between 700 and 1050 F for about 30 min is recommended after moderate or severe forming operations.

The removal of scale after hot forming or stress relieving may be required, depending on the application or subsequent operations such as spot welding, which requires a clean surface. Descaling also facilitates inspection.

Metal Preparation. Titanium blanks may be prepared for forming by shearing, sawing, nibbling or blanking. Material up to 0.187 in. thick has been sheared on flat bed shears rated for 7-0 gage mild steel. Edge cracking in the plane of the sheet can be minimized by sharp shear blades, close tolerance between blade and bed, and by hot shearing. Nibbling is satisfactory for unalloyed titanium but leaves an irregular edge which usually requires an additional smoothing operation. Blanking dies have been used satisfactorily on material up to 0.071 in. thick.

Because of the apparent notch sensitivity of titanium, careful attention must be given to the edge condition of blanks before forming. Deburring is a minimum requirement; on the more difficult forming operations, filing or polishing cut edges may be necessary.

Bending. Depending on the type of equipment (V-block and V-punch, wrap bend, or power brake) bend radii as shown in Table I may be used on sheet 0.020 to 0.125 in. thick.

Most production bending has been

work are more troublesome with titanium than with stainless steels. As a general-purpose die material, high-carbon high-chromium air-hardening tool steel (Type A1) is recommended. Bronze and beryllium copper inserts or weld deposits at wear points on the die have been used to reduce galling. Another method of reducing galling is to sandwich the titanium between sheets of another material such as 1010 steel or aluminum.

Lubricants are mandatory. Molybdenum sulfide, waxes and phosphate coatings are preferred to greases and other petroleum lubricants, particularly for hot forming.

Ratios of depth to diameter as high as 0.66 have been attained on very thin (0.016-in.) unalloyed titanium sheet, to form cylindrical cups in a single operation at room temperature. Temperatures of 600 to 1000 F in drawing operations have proved successful. However, deeper draws can be achieved with multiple-stage dies and intermediate annealing in a muffle furnace with air atmosphere, at 1050 F for 20 to 30 min.

Hydroform-type machines which produce controllable, high, uniform unit pressures are especially adaptable to drawing titanium. Very successful results have been obtained with such equipment at room temperature to produce a wide variety of shapes. A further advantage is that lubrication is not such a crucial factor. A disadvantage is that the platen or working area is small in comparison with the over-all size of the press.

Stretch Forming. Stretch-wrap forming has shown a definite advantage over other methods because it avoids compression wrinkles. A further advantage is the elimination of expensive matched-die tooling.

Stretch forming is by far the best method of making double-curved parts such as airplane fuselage skins. It is also frequently used on curved angles

Table I. Radii for 105° Bends, in Terms of Thickness, t

Thickness of Sheet	Titanium	
	0.020 to 0.070 in.	0.070 to 0.125 in.
Unalloyed (50,000 psi yield strength)	$\frac{1}{2} t$ to $2t$	1 to $3t$
Unalloyed (70,000 psi yield strength)	1 to $3t$	2 to $4t$
Ti-8 Mn (110,000 psi yield strength)	2 to $4t$	3 to $5t$

Caution is necessary in extrapolating the results of bend tests on specimens 1 to 2 in. wide to brake bends of 1 ft or longer, which may require an extra allowance of $\frac{1}{2}$ or $1t$.

done on ordinary power brakes, using conventional male punch and female channel dies. A nominal channel width is $4R + 2t$ (where R = bend or punch radius and t = sheet thickness).

Directional effects are pronounced. When the axis of bend is parallel to the direction of rolling, radii toward the high side of those in Table I may be expected. When the bend axis is perpendicular to the rolling direction, radii on the low side of the tabulated ranges can be attained.

Blanks have been heated between 500 and 1000 F for brake forming, particularly on long bends and thicker material.

Drawing. The rate of forming is important in drawing operations; hydraulic presses with a slow rate of forming have proved superior to mechanical crank-type presses.

Die wear and galling of the die and

and channels, which are first bent on a power brake and then stretched to contour. Annealing at 1050 F for 20 to 30 min between brake forming and stretching, and between successive stages of stretching on some parts, has been used to good advantage.

The narrow spread between yield and tensile strengths of titanium may cause difficulty but when the forming pressures are properly controlled, titanium stretches satisfactorily. Filing or polishing of cut edges is necessary before stretch forming because of notch sensitivity of the metal.

Most stretch forming has been done at room temperature. Both resistance and conduction heating have been used at 500 to 1000 F, with encouraging results, although necking caused by uneven heating is a problem.

Drop Hammer Forming. For complex contoured sheet metal parts, drop ham-

mer forming is the most widely used method. Heated blanks are essential—metal temperatures of 500 to 1000 F are recommended. Heated dies, though difficult to use, are desirable, to prevent chilling of the hot blanks. Annealing, as described under Drawing, may be used to advantage on some parts.

Zinc alloy dies are acceptable for hot forming a limited number of parts. Die materials more resistant to wear, brinelling, and the forming temperature are needed for larger production quantities; gray iron, nodular iron and steel have been used successfully.

Forming in Rubber. The Guerin (rubber pad) method of forming on hydraulic presses is useful for simple forming of light gage parts. Unit pressures of 1400 to 8700 psi are being employed, with better results at the higher pressures. Both zinc alloy and steel dies have been used successfully.

Limitations are encountered in the formation of convex (shrink) flanges because of compression wrinkles. Auxiliary equipment such as wedges, clips and draw rings helps to overcome these limitations and increases the versatility of the process.

Temperatures of 500 to 1000 F are useful in this method, primarily through lowering the yield strength and increasing the ductility of the work. Steel dies and heat-resistant rubber pads should be employed; additional protection may be obtained by sprinkling powdered asbestos over the hot blank.

Dimpling. Both alloyed and unalloyed titanium have been dimpled in gages up to 0.065 in. on ram-coin dimpling machines, using dies heated to 750 F. In addition to the normal time delay while the machine is building up pressure, a dwell time of 2 sec is utilized to provide sufficient heat in the sheet prior to dimpling. Close inspection is necessary to reveal fine, irregular, circumferential cracks.

Joggling. Joggling is the offsetting of a small portion of a metal part (an angle or a flange, for example) so that the joggled section will clear adjoining parts or will fit flush with another part attached by a lap joint. Titanium and titanium alloys can be joggled readily at room temperature. Ratios of joggle runout to depth (ratio of length to offset) can be obtained which compare favorably with the ratio (8 to 1) normally used for 1/2-hard 18-8 stainless steel. Lower ratios (4 or 5 to 1) can be obtained by heating the dies or parts or both.

Machining and Grinding

Alloy titanium is difficult to machine because: (1) titanium carbides, when present, are harder than the carbides in the cutting tool; (2) titanium glazes and smears on a cutting tool, resulting in immediate tool breakdown; (3) the low volumetric specific heat and thermal conductivity of titanium cause excessive heating at the tool-chip interface, resulting in rapid deterioration of the cutting edge; (4) the low modulus of elasticity necessitates back-up bars or special fixtures if proper tolerances and the desired surface finish are to be obtained; and (5) abrasive oxides form on titanium when it is heated in air, and by diffusion a hard zone may be produced beneath the scale.

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speed steel are required. Each tooth should carry a chip load of 0.002 to 0.006 in. Chip breakers should not be used; they increase the cost of broach maintenance greatly. Clearances of 1 to 2 deg are normal.

Milling. High speed steel cutters having 0 deg rake, 0.010 to 0.015 in. land, 3 deg relief are being used successfully. Carbide-insert cutters with 10 deg axial rake, 0 deg radial rake and each tooth set 3/32 in. ahead of the center line show excellent life. A tooth load of 0.005 in., downfeed from 0.025 to 0.050 in. and surface speed of 53 fpm give good tool life. Sulfurized oils and water-soluble oils have been used.

Sawing. Titanium can be cut satisfactorily on conventional power hack saws if the blade is not allowed to ride the work and if fairly heavy pressures are used. On friction-feed saws, a high speed steel blade with six teeth per inch is satisfactory with a feed of 0.015 in. With a positive hydraulic feed of 0.009 to 0.012 in., blades having two to four teeth per inch and rounded gullets have given most satisfactory results. A flood of standard cutting oil is a good coolant.

Grinding. Speeds lower than on steel give grinding ratios about the same as those obtained in grinding high speed steel. When grinding at low speeds (about 1600 fpm) aluminum oxide wheels with coarse grain size (60) and medium hardness (M) give good results in conjunction with a water-soluble coolant of the sodium nitrate-amine type in 10 to 1 ratio. In plunge grinding of titanium at 6000 fpm, a silicon carbide wheel of medium grain size and high hardness (P) with the same coolant has been satisfactory. Soluble oils are applicable. Straight grinding oils can be used but there is a fire hazard at high grinding speeds.

Welding

Titanium and some titanium alloys can be joined by inert-gas-shielded arc welding and resistance welding. Oxyacetylene and metal-arc welding with coated electrodes are impractical.

Unalloyed titanium and the higher-strength all-alpha alloys generally produce welds with nearly the same strength and ductility as the base metal; this is true of both the Ti-Al and Ti-Al-Sn alloys. The alpha-beta alloys containing less than 3% of beta-stabilizing elements also generally produce ductile welds. As alloy content increases in alpha-beta alloys, the welds are less ductile because of the transformation of beta on cooling. Ductility can usually be improved by post-weld heat treatment.

Table II. Recommendations for Turning Titanium

Tool material	Rough Turning		Finish Turning, Unalloyed Titanium ^(b)
	Unalloyed Titanium	Forged Alloy ^(a)	
HSS ^(c)	Carbide	Carbide	Carbide
Min feed, in. per rev	0.040	0.015	0.008
Speed, fpm	20 to 30	40 to 65	30 to 65
Side cutting edge angle, deg	15 to 20	15 to 20	30 to 45
Side rake angle, deg	8	4	6
End relief angle, deg	7 to 8	7 to 8	10 to 12
Min nose radius, in.	1/8	1/8	1/8
Coolant	Water-soluble coolants should be used in 10 to 1 ratio.		

(a) Alloy of 140,000 psi tensile strength. (b) Forged alloy same except speed 65 to 150 fpm and side cutting edge angle 30 to 45 deg. (c) High speed steel of high vanadium or high cobalt content or both.

Table III. Typical Data for Inert-Gas-Shielded Arc Welding of Titanium

	Tungsten Electrode	Consumable Electrode
Electrode	Tungsten, $\frac{1}{16}$ to $\frac{1}{8}$ in. diam	Bare titanium wire, $\frac{1}{16}$ in. diam
Shielding gas	Argon or helium, 15 to 35 cu ft per hr (adjusted to give shiny weld-metal surface)	Argon-helium mixture, 60 to 100 cu ft per hr, 30 argon, 70 helium, trailing shield, 30 to 100 cu ft per hr
Travel speed	4 to 25 in. per min	10 to 20 in. per min
Welding current	D-c electrode negative, 100 to 150 amp at 18 to 26 arc volts	D-c electrode positive, 300 to 450 amp at 30 to 35 arc volts
Base-metal thickness	$\frac{1}{16}$ to $\frac{1}{2}$ in.	$\frac{1}{16}$ to $\frac{1}{2}$ in.
Type of joint	$\frac{1}{16}$ to $\frac{1}{8}$ in. square butt or single vee, $\frac{1}{16}$ to $\frac{1}{2}$ in., single or double vee	Single or double vee, 70 to 90 deg included angle, single or multi-layer welds

Inert-Gas-Shielded Arc Welding. Titanium must be protected from oxygen and nitrogen while being welded. Procedures have been developed for manual and automatic welding, both with tungsten and consumable electrodes (Table III). A water-cooled copper back-up may provide some protection but an inert-gas-shield back-up is usually necessary. A trailing shield to provide an inert cover over the hot weld area is recommended, particularly when welding at high travel speeds with a consumable electrode.

Spot and Seam Welding. Satisfactory spot and seam welds can be made in unalloyed titanium, the higher-strength all-alpha alloys and the low-alloy alpha-beta alloys, using standard equipment and procedures (Table IV). Because of the short welding time and the proximity of the sheets being welded, an inert atmosphere is unnecessary. Clean, as-rolled titanium welds readily. Annealing scale and hot forming oxides must be removed. Under most conditions high-strength welds with moderate ductility can be obtained. A ductility ratio (tensile to shear strength) of 0.25 to 0.40 can be expected with unalloyed titanium. Lower ratios are obtained with titanium alloys.

Flash Welding. Ductile flash welds can be made without shielding in the weldable alloys but when made in an inert atmosphere they have somewhat higher ductility.

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Heat Treating

The only heat treatments now commercially feasible for titanium are the stabilizing of forged parts at 1100 to 1300 F and the stress relieving of machined units and formed sheet metal articles between 700 and 1050 F. Full softening of alloyed and unalloyed sheet requires an anneal at about 1100 to 1300 F. Titanium alloys are usually shipped from the mills in the stabilized condition.

quent salt bath or acid pickling is recommended to remove such particles, lest they cause surface defects. Wire brushing should also be done with caution to prevent iron pickup.

Surface hardening with oxygen, nitrogen or carbon, or combinations of these, and by cyaniding, anodizing, chemical coating, or electroplating with other metals, are often suggested to decrease seizing and galling of titanium surfaces subject to frictional loads. All of these methods are in the development stage. The three mentioned last seem to be the most promising and practical at this time. Chromium plating has been successful on a small scale. Chemical coatings and anodizing have been reported to aid paint adhesion and to serve as a base for lubricants in drawing and forming.

Corrosion Resistance

Titanium has outstanding resistance to natural environments and to many chemicals. This resistance is usually attributed to a protective oxide or adsorbed-oxygen film and, in general, is enhanced by oxidizing agents. Where attack is observed, corrosion is uniform and generally little or no evidence of pitting or other form of localized attack is found. Commercial grades of the metal have been tested successfully in a variety of chemical, pharmaceutical, food processing and marine applications where high resistance is required.

The following paragraphs summarize the effects of the more important environments on unalloyed commercial titanium, as indicated by results of laboratory tests.

Chloride and Hypochlorite Salts. Unalloyed titanium has excellent resistance to cold and hot chloride solutions of all concentrations; only one exception is known—hot concentrated solutions of aluminum chloride. Corrosion rates of less than 0.15 mpy (mils penetration per year) were reported for boiling solutions of the very corrosive cupric and ferric chlorides and sodium and calcium hypochlorites. Negligible attack and no evidence of stress corrosion was observed on highly stressed titanium exposed to boiling solutions of cupric, ferric, magnesium, mercuric, mercurous, nickel, silver, sodium and zinc chlorides.

Chlorine Gas. Except for slight staining, massive titanium appears to be completely immune to chlorine gas containing more than 0.013% by weight of water. However, titanium chips may ignite in chlorine containing less than 0.005% water.

Chromic Acid. Hot solutions of chromic acid have little effect on titanium. The maximum corrosion rate was 1.8 mpy in a 36.5% acid at 194 F.

Hydrochloric Acid. Titanium dissolves slowly in dilute HCl solutions at moderate temperatures. Rates of nil to 42 mpy were observed in hot or concentrated solutions. The metal is made passive in HCl by traces of oxidizing

Table IV. Spotweld Data for Unalloyed Titanium

Sheet Thickness, in.	Weld Force, lb	Weld Time Cycles	Weld Current, amp	Shear Strength, lb per spot	Nugget Diameter, in.
0.020	300	3	3000 to 6000	700 to 1000	0.08 to 0.12
0.032	500	5	4000 to 7000	1300 to 1600	0.10 to 0.16
0.040	600	6	5000 to 9000	1600 to 2000	0.12 to 0.20
0.064	1000	10	6000 to 11,000	2600 to 3200	0.15 to 0.30

agents such as dissolved oxygen, HNO_3 , potassium dichromate and ferric and cupric chlorides. For example, 0.2 g per liter of copper (as cupric chloride) was found to inhibit corrosion in a 37% solution, and a solution of 1% HNO_3 and 20% HCl gave a corrosion rate of only 0.14 mpy at 95°F.

Hydrofluoric Acid. Titanium is attacked by all concentrations of HF. Unlike corrosion in other mineral acids, HF corrosion is not inhibited by oxidizing agents.

Hydrogen Peroxide. Except for slight staining, titanium appears to be unaffected by 3 and 6% H_2O_2 . Tests in a 30% solution yielded rates of less than 5 mpy but tests in sealed tubes gave rates less than 1 mpy.

Hydroxides. Boiling solutions of 20% NH_4OH and 10% NaOH and KOH had a negligible effect on titanium. A 40% solution of NaOH at 176°F gave a rate of 5 mpy.

Nitric Acid. Nitric acid in all concentrations, including 98%, has a negligible effect on titanium at moderate temperatures, and the metal has very good resistance to all hot solutions. For example, rates under 5 mpy have been reported for boiling 65% acid and for this acid under equilibrium pressures up to 330°F.

Hot red and white fuming nitric acid attack titanium at a negligible rate. The highest rate observed was 0.26 mpy in a boiling mixture of the red and white acids. However, highly stressed titanium suffers from stress corrosion in the red acid. In this solution cracking can be inhibited by a 1% addition of sodium bromide.

CAUTION: Titanium and titanium alloys are not recommended for use in fuming nitric acid. Several unexplained explosions have occurred with stressed unalloyed titanium and with a titanium-manganese alloy when test specimens were immersed in red fuming nitric acid for extended periods.

Phosphoric Acid. Titanium corrodes at less than 2 mpy in aerated solutions of 30% phosphoric acid at room temperature; the rate increases to about 30 mpy in the 85% acid. The rate of attack is increased with temperature but corrosion can be partially inhibited by oxidizing agents, as chromic acid.

Sulfur and Sulfur Compounds. Water saturated with H_2S or SO_2 has no noticeable effect on titanium. The metal acquires a thin blue film but loses no weight during prolonged immersion in molten sulfur at 465°F.

Sulfuric Acid. Titanium has good resistance to H_2SO_4 solutions up to 5% at 95°F and 1% solutions at 185°F but attack is rapid at higher temperatures and concentrations. Corrosion in H_2SO_4 is also inhibited by the presence of oxidizing agents. For example, 1% HNO_3 added to concentrated H_2SO_4 at 95°F reduced the corrosion rate from 216 to 10.6 mpy, and a 50% H_2SO_4 solution containing from 1/2 to 3% HNO_3 at 120 to 140°F gave rates of 2 mpy. The resistance to H_2SO_4 solutions up to 55% is greatly improved by anodizing; for example anodizing decreased the rate of attack from 237 to 0.64 mpy in a 39% solution at 95°F.

Organic Chemicals and Food Products.

Unalloyed titanium has excellent resistance to many organic acids, including hot solutions of acetic, citric, chloroacetic, dichloro-acetic, lactic, tannic, stearic, tartaric and aerated formic acids of high and low concentrations. However, hot nonaerated solutions of 25 and 50% formic, 100% trichloro-acetic and all concentrations of oxalic acid attack the metal. Titanium seems to be completely unaffected by chlorinated hydrocarbons and by the common fruit and vegetable juices. The metal is being used successfully in equipment for the synthesis of urea.

Sea Water and Other Natural Environments.

Unalloyed titanium exposed to industrial, rural and marine atmospheres for five years retained its original luster and appeared to be completely unaffected. Tarnishing occurs at elevated temperatures but this is not a problem within the temperature range in which the mechanical properties of the metal permit its use.

Exposures up to five years in sea air and sea water under all the test conditions available at the Inco Harbor Island and Kure Beach Test Stations had no significant effect on titanium. No evidence of stress corrosion, corrosion fatigue, galvanic corrosion, pitting, crevice corrosion, erosion corrosion or any other form of attack was observed. For example, titanium with a 105,000 psi yield strength at 0.2% offset statically loaded to 80,000 psi is still under test after five years with no sign of failure. The metal has the same fatigue limit of 60,000 psi in air and sea water.

The galvanic effect of titanium coupled to common structural materials is about the same as that of 18-8 stainless steel. In all tests the effect on titanium is negligible. Depending on the other material in the couple, varying effects may be obtained. In particular, aluminum and magnesium may be severely corroded unless they are adequately protected, as by organic coatings; preferably, they should be electrically insulated from the titanium.

Metallography

Titanium has a greater tendency than most metals to drag or bind during cutting. In the preparation of metallographic specimens, the surface must be fine-cut with little or no smearing of the metal by the cutting edge. Silicon carbide is the most satisfactory cut-off wheel. To avoid overheating and distortion, the specimen should be flooded under a constant stream of water.

Grinding. Silicon carbide abrasive is superior to the more commonly used emery. Grades 240, 400 and 600 are recommended. Papers or belts should be

lubricated with water or oil to facilitate cutting and prevent overheating. A small belt grinder with a lubricant recirculating system is very satisfactory for grades 240 and 400. Fine grinding on 600 paper is done by hand with the paper resting on glass and moistened with water.

Polishing Procedure 1. Polishing of a carefully ground surface presents little difficulty. Four short steps on cloth-covered slowly rotating laps are recommended:

- 1 45 to 60 sec using 8 to 20 micron diamond dust compound on an airplane-wing cloth (or a fine cotton broadcloth)
- 2 45 sec using 8 to 20 micron diamond dust compound on Gamal cloth
- 3 45 sec using 0 to 2 micron diamond dust compound on Gamal cloth
- 4 60 sec using 0.3 micron aluminum oxide on Gamal cloth

If fine scratches persist, a fifth step using 0.1 micron aluminum oxide on Gamal cloth for 60 sec may be necessary. Repolishing on the last cloth is usual after etching. For unalloyed titanium, which has a greater tendency to flow, more than one such repolish may be necessary.

Polishing Procedure 2. The following procedure may be used with success if it is not desired to use diamond dust as a polishing medium:

- 1 Coarse polish on revolving lap covered with airplane-wing cloth using 0.3 micron aluminum oxide as the abrasive
- 2 Final polish with 0.1 micron aluminum oxide on Gamal cloth

Water with a small amount of liquid soap may be used as a lubricant. A few drops of a 5% solution of oxalic acid in water may be added during the final polish to help prevent surface flow. As pointed out in Procedure 1, a second final polish after etching may be necessary to remove flowed metal.

Procedure 2 is usually satisfactory for titanium alloys while Procedure 1 is more satisfactory for the softer unalloyed commercial titanium on which flowed metal is more easily produced.

Electropolishing. Electropolishing with a perchloric acid and acetic anhydride electrolyte has been used successfully. Typical compositions are given by P. Jacquet in Metal Treatment and Drop Forging, April 1951, p 176.

The following electrolyte, which is nonexplosive, is recommended:

- 90 ml ethyl alcohol (absolute or No. 30 denatured)
- 10 ml n-butyl alcohol
- 6 g aluminum chloride (exothermic solution, add slowly)
- 25 g zinc chloride

The salts are dissolved in the alcohol in the order given; the solution must be cooled during mixing, since considerable heat is evolved. The solution is

Table V. Etching Reagents for Titanium and Titanium Alloys

Concentration	Use	Procedure
HF (48%)—1 part by vol Glycerol—1 part by vol	Darkens alpha but not beta	Swab or immerse 1 to 10 sec
HF (48%)—2 ml Water—98 ml	Darkens alpha but not beta	Swab or immerse 5 to 25 sec
HF (48%)—1 part by vol HNO_3 (conc)—1 part by vol Glycerol—2 parts by vol	Alpha and beta both light; nitric acid brightens surface and removes residue	Swab or immerse 1 to 10 sec
HF (48%)—1 ml HNO_3 (conc)—12 ml Water—87 ml	Etches alpha and beta light; nitric acid brightens surface	Swab or immerse 10 to 30 sec

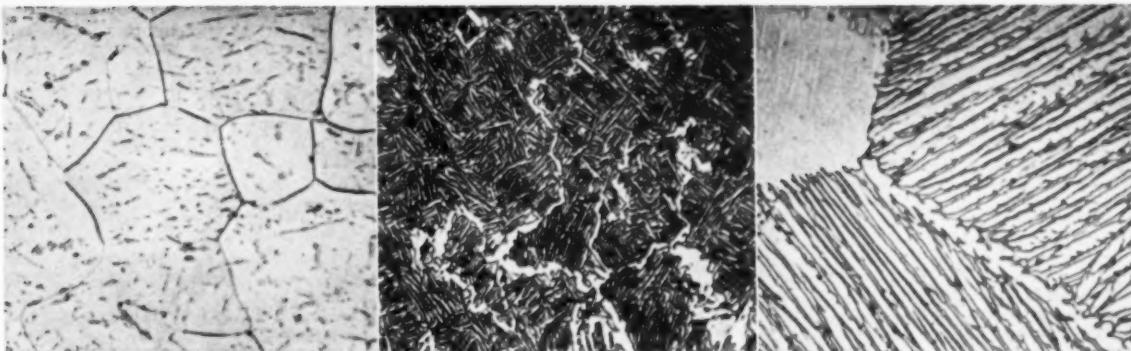


Fig. 1. Typical Microstructures of Commercial Titanium and Titanium Alloys Prepared According to the Recommended Metallographic Procedures ($\times 500$). Left—Commercial unalloyed titanium of intermediate hydrogen content, annealed at 1300 F, air cooled, precipitate of

titanium hydride. Center—Alpha-beta type alloy containing 2% Fe, 2% Cr and 2% Mo, finish forged high in the alpha-beta field, annealed at 1100 F, air cooled. Right—Alpha-beta type alloy containing 27% Cr and 13% Fe, furnace cooled from the beta field.

stable for about one week. Electro-polishing conditions are as follows: 30 to 60 volts dc; 1 to 5 amp per sq in. of anode (the specimen); stainless steel or other suitable cathode; 1 to 6 min; 75 to 85 F; solution agitated.

The following electrolyte has also been used successfully, but is less attractive because it heats rapidly during polishing: 80 ml glycerine; 5 g barium fluoride; 5 ml conc H_2SO_4 ; 2 amp per sq in.; 90 volts; 1 to 2 min.

Etching. The majority of the commonly used chemical etching agents for titanium contain hydrofluoric acid as the principal ingredient. Nitric acid may be added to minimize staining and brighten the surface. The reagents may be in a water or glycerol solution with glycerol used to inhibit pitting of the surface.

Table V lists some of the common etching reagents, together with their characteristics. The same reagents may be used for revealing macrostructure with somewhat longer etching times. Wetting with India ink and wiping lightly will help to increase contrast in macro-etching.

The concentration of acids in the $HF-HNO_3$ reagents may be varied substantially from those given and equally good results obtained when compensating changes are made in etching time.

Heat Tinting. Heating polished and etched specimens at about 1000 F for 1 min has been used to distinguish between alpha and retained beta. Under these conditions, retained beta appears deep violet to bright blue, and transformed beta (isothermal or equi-axed alpha) is dull yellow to golden yellow, with some violet coloring.

Microstructure. The microstructure of titanium and titanium alloys is principally influenced by the allotropic transformation which it undergoes, at about 1625 F, from the close-packed hexagonal alpha phase to the body-centered cubic beta phase. The majority of the commercial alloys now in production are of the alpha-beta type and, as hot worked and annealed, consist of a mixture of alpha plus beta of sufficiently high alloy content to be retained to room temperature.

A great variety of microstructures can be produced by changes in heat treatment and hot working schedules. Present commercial treatments produce microstructures similar to those shown in Fig. 1.

Applications

Virtually all titanium is being used today because of its favorable ratio of strength to weight between 300 and 700 F. It also has corrosion resistance equal or superior to 18-8 stainless steel in most media, and notably in marine exposure. This combination makes titanium unique.

Like other metals, titanium would be used more if it cost less. It has cost 30 to 40 times as much as the stainless steel which it has replaced.

Titanium is available in the form of sheet, bar and forgings; it has been produced less extensively as tubing, plate and wire; experimental extrusions and castings have been made.

Following are some current uses:

Aircraft Gas Turbines. The chief usage in turbo-jet and turbo-prop engines is as bar stock and forgings. These are used in making compressor disks, spacer rings, rotating and stationary compressor blades and vanes, through bolts, turbine housings and liners, and miscellaneous hardware. Titanium sheet is used for fire shields, brackets and shroud stock.

Airframes. Titanium and titanium alloy sheet are being used in airframes for both structural and nonstructural applications, primarily surrounding engines, where service temperatures are in the range from 300 to 700 F. Because aluminum alloys are generally more efficient than titanium below 300 F, titanium is not used significantly for wings and other unheated structures. Above 700 F, stainless steel becomes more efficient.

Titanium landing gears have been studied and built experimentally; however, alloy steels, heat treated to a tensile strength between 200,000 and 280,000 psi, are preferred. The lower modulus of titanium is also a deterrent for this application.

Titanium is being used in both military and commercial aircraft. Even in the latter, the savings in weight and the accompanying extra pay load justify the present high initial cost.

Fasteners. Titanium and titanium alloy rivets, nuts, bolts and screws have been manufactured in a variety of sizes, principally for evaluation. The high-shear type of rivet on which stainless steel or Monel clips or collars are swaged looks promising. Shear-type fasteners may be important in design because of the relatively high shear-

tensile ratio of titanium. Titanium alloy screws and particularly bolts also offer possibilities for saving weight.

Other Applications. Because of superior corrosion resistance, titanium and titanium alloys are being used experimentally in several shipboard applications—for example, seats and disks in globe valves and metering disks in displacement-type fuel systems. Certain items of military equipment which must be light for mobility or air-transportability have been made experimentally from titanium. Some titanium is being used in the chemical industry for pipe and fittings to carry highly corrosive chemicals; consideration is also being given to its use for light-weight storage tanks for liquefied gases.

Design

Designing with titanium is similar to designing with aluminum or stainless steel. For example, as with aluminum, allowance must be made for its low modulus of elasticity where this is a factor, but worked and formed parts are similar to stainless steel (see page 81). The ratio of fatigue limit of unnotched specimens to tensile strength is more like that of steels than of the light alloys and under certain conditions the ratio is appreciably higher than for either of these groups. Obviously, generalizations may be hazardous.

One of the important disadvantages of titanium is its tendency toward galling when rubbed against itself or other metals. For this reason it is not suitable for bearings or parts requiring low frictional wear. Plating with chromium, coating with a suitable plastic, and surface treatments such as nitriding may be helpful; plating techniques seem to be the closest to early application.

Designers should try to avoid shapes which require extensive or intricate machining operations. Although titanium does not machine well, it is forgeable and the use of die forgings or semi-forged billets may minimize machining costs. Titanium sheet is difficult to shrink in forming, and shrink flanges should be avoided.

Vibration and damping characteristics are of great significance in the important application of gas turbine compressors. In the design of a compressor rotating wheel for a gas turbine (consisting of a steel disk and steel blades), titanium cannot be substituted

for the steel disk without a change in design because the natural frequency of the disk would be lowered enough so that it could be in resonance with the engine running speed. However, if titanium blades are used with a titanium disk and both are designed the same as the steel parts, the frequency of the resulting part will be the same as the frequency of the steel assembly. This is true because the frequency of any part is proportional to the geometry, modulus of elasticity and density of the material. The effect of the combination of modulus and density of steel is the same as with titanium.

Damping capacity is important because, in gas turbines, excessive aerodynamically-induced vibrations are damped out by the combination of material damping and frictional damping in the mechanical fastening of the blade and disk. When titanium alloys are considered for compressor blading, the lower damping capacity must be offset by an increased damping between blade root and disk. If this is not done, premature fatigue failures will result.

Where stiffness and rigidity are controlling factors, an increase in section thickness may be required to compensate for the low modulus of elasticity of titanium. This could more than offset the weight savings calculated from considerations of tensile strength alone.

Selection of Alloys

Current titanium alloys are the so-called commercially pure or unalloyed type (alpha single-phase), the alpha-stabilized or all-alpha alloys, and the alpha-beta two-phase alloys. The unalloyed metal is primarily titanium with small amounts (usually less than 0.1% each) of carbon, oxygen and nitrogen. Present commercial all-alpha alloys contain aluminum as the primary alloying element, with or without tin as a secondary addition. The alpha-beta alloys contain various proportions and combinations of manganese, chromium, molybdenum, iron, vanadium and aluminum; carbon, oxygen and nitrogen are also present—usually in residual amounts, sometimes intentionally.

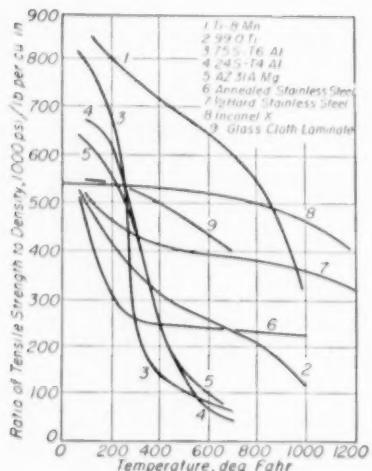


Fig. 2. Approximate Comparison of Materials on a Strength-Weight Basis from Room Temperature to 1000 F (K. A. Wilhelm)

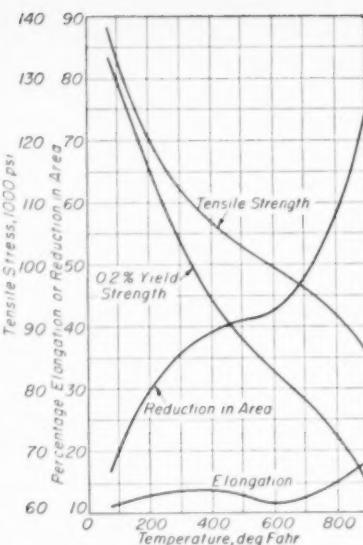


Fig. 3. Average Short-Time Mechanical Properties of Titanium Alloy Forged Disk at Elevated Temperatures. Alloy contains 4% Al and 4% Mn

Properties. Numerical values for the properties of titanium and commercial titanium alloys are tabulated on pages 87 to 89, according to the standard arrangement used in the Nonferrous Section of the 1948 ASM Metals Handbook. Some general relations among the properties most important in design are discussed here.

Titanium lies between aluminum and steel in density, strength, modulus of elasticity and serviceability at elevated temperatures. The density of titanium alloys is about 40% less than for austenitic stainless steel and 70% greater than for aluminum alloys.

The coefficient of thermal expansion of titanium alloys is about 40% less than for austenitic stainless steel. In general, the thermal expansion of titanium alloys increases with alloying. In composite structures of titanium with other metals, the low expansion may introduce undesirable thermal stresses.

The thermal conductivity of titanium alloys is approximately the same as for austenitic stainless steel and varies about 25%, depending on alloying constituents. This low conductivity may result in local hot spots in heated structures; on the other hand, a limited insulating effect may be considered as an advantage in certain applications.

The electrical resistivity of titanium alloys is high—roughly equivalent to austenitic stainless steel. Alloying additions cause an increase and may result in extremely high resistivities which might prove useful in electrical applications. The high resistivity is also useful as a means of heating for hot forging.

Titanium is nonmagnetic.

Despite early conflicting reports, it has become increasingly clear that titanium and its alloys have good fatigue resistance in the unnotched condition. For example, ratios of fatigue limit to tensile strength as high as 0.85 have been reported, with minimum values near 0.55, compared with nominal values near 0.5 for steel and 0.3 for the

light alloys. For notched specimens, results vary markedly. With sharpest notches, titanium seems to be greatly inferior to steel. With rounder notches, this deficiency tends to disappear and under some notch conditions titanium may even be superior to other metals. In applications where notch fatigue is important, detailed and specific tests should be conducted. At sub-zero temperatures, the fatigue limit of titanium improves.

Low-Temperature Properties. Meager data on the low-temperature properties of titanium and its alloys indicate an increase in hardness and tensile strength as temperature is lowered from room temperature; elongation decreases with lower temperatures; notch sensitivity appears to increase.

Elevated-Temperature Properties. The weight advantage of titanium between 300 and 700 F is well illustrated by Fig. 2. Between 800 and 1000 F, the strength of alpha-beta titanium alloys decreases rapidly; the all-alpha alloys are stronger in this range (see table, page 89). Oxygen and nitrogen begin to be absorbed irreversibly in short-time exposure at about 1300 and 1500 F, respectively, with consequent embrittlement of the titanium surface. During prolonged exposure, appreciable pickup of oxygen may occur at 800 to 1000 F. Figures 3 and 4 give more detailed data for temperature effects in a typical high-strength titanium alloy and in unalloyed titanium.

The discussion thus far has dealt with short-time mechanical properties. As the intervals during which the loads are applied become greater, extending to hours and hundreds of hours, the strength decreases. In designing for sustained loads at elevated temperatures, the creep characteristics of titanium are more important than the yield strength under some conditions. As shown by the curves on pages 88 and 89, minimum creep rate does not follow yield strength. At temperatures above about 700 F (which varies somewhat among different alloys), stresses considerably below the yield strength will produce plastic deformation, which increases rapidly with increasing time under load.

Unalloyed titanium (not alloys) deforms plastically under stresses lower

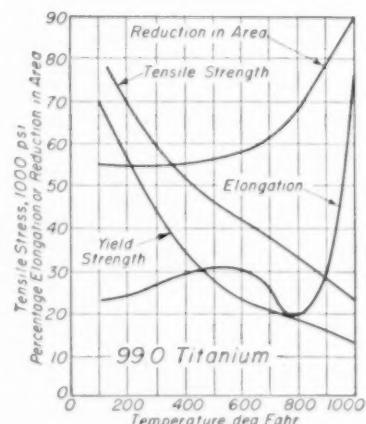


Fig. 4. Average Short-Time Mechanical Properties of Unalloyed Titanium at Elevated Temperatures (K. A. Wilhelm)

Table VI. Ranges for Mechanical Properties at Room Temperature^(a)

Product	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., %
Sheet, Strip and Plate			
Unalloyed (high ductility)	60 to 80	40 to 70	20 to 30
Unalloyed (high strength)	80 to 110	70 to 100	15 to 25
Ti-O-N	100 to 120	90 to 110	15 to 20
Ti-5 Al-2.5 Sn	120 to 140	110 to 130	15 to 20
Ti-8 Mn	120 to 150	110 to 140	10 to 20
Ti-2 Fe-2 Cr-2 Mo	130 to 150	120 to 135	12 to 18
Forgings, Bars and Rods			
Unalloyed (high ductility)	60 to 85	40 to 75	20 to 30
Unalloyed (high strength)	80 to 115	70 to 105	15 to 25
Ti-O-N	100 to 120	90 to 110	15 to 20
Ti-5 Al-2.5 Sn	120 to 140	110 to 130	15 to 20
Ti-2 Fe-2 Cr-2 Mo	130 to 150	120 to 135	12 to 18
Ti-4 Al-4 Mn	140 to 160	130 to 150	12 to 20
Ti-2.7 Cr-1.3 Fe-O	140 to 160	130 to 145	12 to 18
Ti-3 Al-5 Cr	145 to 170	130 to 160	10 to 18

Modulus of Elasticity, 15,000,000 psi

(a) The lower figure represents the guaranteed minimum for the property; the range indicates the expected variation, including effects caused by section thickness.

than the yield strength at room temperature and at temperatures up to approximately 300 F. Between about 300 and 700 F, the elevated-temperature yield strength of titanium can be used as the design strength criterion. The room-temperature creep of unalloyed titanium is unimportant in most elevated-temperature designs.

Selection. Unalloyed titanium, as would be expected, has the lowest strength in the group (Table VI). Currently, it is used mainly as sheet in applications where light weight and either corrosion resistance or heat re-

sistance are important but where strength is secondary—as in nonstructural aircraft items such as shrouds, firewalls and hot gas ducts, where annealed stainless steel would normally be used. Various grades of unalloyed titanium sheet are available, and selection is based on the desired strength, ductility, formability, permissible bend radii and similar characteristics.

Titanium alloys are generally graded by strength, as in Table VI. Currently, only one alpha alloy is available, in the form of billets, bars, plates and heavier sheet, and should be consid-

ered where weldability is important, together with higher strength than is available in unalloyed titanium, or where retention of strength at high temperature is especially important. A further consideration is the limited formability of the alpha alloy sheet products, as compared with unalloyed or alpha-beta alloy sheet.

The remaining commercial alloys are of the alpha-beta type and selection is dictated by one or more of these factors: strength-weight ratio at operating temperature, hardness, ductility, section size, forgeability, workability, creep resistance, stress to rupture, notch sensitivity, impact, fatigue, damping, directionality, weldability and others. Once it has been decided to use some titanium alloy, the above factors are more important than resistance to corrosion, wear, galling, and physical properties such as thermal conductivity, since these latter characteristics vary less from one titanium alloy to another than do the other properties mentioned.

Where maximum weight must be saved, it is important to consider for each likely alloy the property most critical in a particular design—for example, tension, compression, shear or rigidity. The strength-weight advantage with titanium will vary depending on the property concerned; weight savings which might be indicated by a superficial examination of tensile strength, often used as a criterion, may not materialize when a detailed design study is made.

PROPERTIES OF TITANIUM AND TITANIUM ALLOYS

Titanium (99.9 Ti)

A 1 Common name. Iodide titanium

3 ASTM number. B266-52T

B 1 Typical uses. For experimentation and research on titanium properties and alloys; for commercial applications requiring maximum ductility and formability and freedom from interstitial alloying elements (oxygen, nitrogen, carbon and hydrogen)

C 1 Density at 20 C (68 F), 4.507 g per cu cm (0.163 lb per cu in.); beta titanium at 885 C (1625 F), 4.31 g per cu cm (0.156 lb per cu in.)

D 1 Melting point. 1670 ± 20 C (3040 ± 35 F)

4 Boiling point at 760 mm Hg, 3260 C (5900 F)

Vapor pressure of beta titanium:

$$\log p(\text{atm}) = 7.7960 - 24.644/T - 0.227 \times 10^{-6}T$$

Vapor pressure of liquid titanium:

$$\log p(\text{atm}) = 6.255 - 22.100/T$$

5 Transformation temperature ($\alpha \rightarrow \beta$), 882 C (1620 F)

6 Thermal expansion.

$$20 \text{ to } 300 \text{ C (68 to 572 F)}: 0.0000082 \text{ per } ^\circ\text{C}$$

12 Specific heat versus temperature. See Fig. 1.

13 Latent heat of fusion. 100 cal per g (est)

14 Latent heat of transformation. 14 cal per g

18 Heat of combustion. 4700 cal per g to TiO_2

E 1 Volume conductivity referred to standard copper, 3.6%

2 Electrical resistivity at 25 C (77 F), 54.98 microhm-cm

5 Temperature coefficient of electrical resistivity, 10 to 30 C (50 to 86 F), 0.00425 per C

16 Superconductivity. Superconductive below 1.73 K

J 1 Crystal structure. Alpha is close-packed hexagonal, stable to 882 C (1620 F); beta is body-centered cubic, stable from 882 C to the melting point.

$$\text{alpha: } a = 2.9504 \text{ kX}; c = 4.6833 \text{ kX}; c/a = 1.587$$

$$\text{beta: } a = 3.3065 \text{ kX}$$

K Mechanical properties.

Tensile strength 36,000 psi

0.2% yield strength 20,000 psi

Elongation in 2 in. 70%

Reduction in area 88%

Vickers hardness 80 to 100

Impact values Above 100 ft-lb down to -321 F

K 2 Directional properties. Little or no effect of working direction on mechanical properties

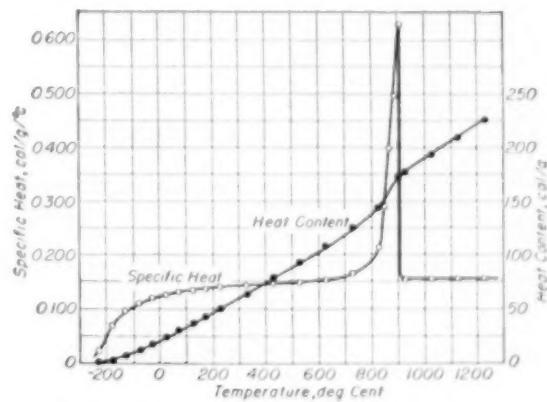


Fig. 1. Heat Capacity and Heat Content of Iodide Titanium

6 Modulus of elasticity versus temperature. Dynamic modulus decreases linearly from 15,400,000 psi at 25°C (77°F) to 9,900,000 psi at 550°C (1022°F); measurements in tension at 25°C, 15,900,000 psi

M 2 Consequences of exceeding impurity limits. Higher hardness, reduced ductility, higher tensile strength
N10 Maximum reduction between anneals. 90% or more

15 Heat treatment. Annealing at 600°C (1100°F) or above will recrystallize cold worked metal.

17 Joining. Arc weld in a protective atmosphere.

M Composition limits (ASTM B265-52T). Components: 99.9% Ti; impurities: 0.03% max C; 0.02% max Si; 0.02% max Fe; 0.03% max Al; 0.01% max N; 0.04% max Mn; 0.01% max O; others (each) 0.01% max

Titanium (99.2 Ti)

A 1 Common name. Unalloyed titanium, 55,000 psi design yield strength

3 ASTM number. B265-52T, grade 2

5 Other designations. AMS 4900

B 1 Typical uses. In sheet form, for applications requiring maximum ductility for fabrication and little strength

C 1 Density. 4.54 g per cu cm (0.164 lb per cu in.)

D 6 Thermal expansion.

20 to 100°C (68 to 212°F). 0.0000090 per °C

20 to 400°C (68 to 750°F). 0.0000095 per °C

20 to 700°C (68 to 1290°F). 0.000010 per °C

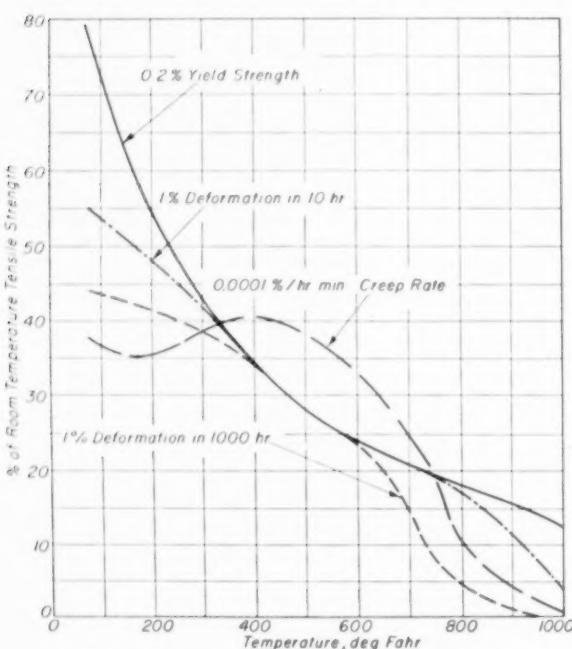


Fig. 1. Creep Properties of Annealed Titanium Sheet (99.2 Ti)

E 2 Electrical resistivity at 20°C (68°F). 55 microhm-cm, annealed

5 Temperature coefficient of electrical resistivity. -18 to 205°C (0 to 400°F). 0.17 per °C

I 2 Resistance to specific agents. See page 83.

K Mechanical properties. See Table I.

6 Creep properties. See Fig. 1 and 2.

M Composition limits (ASTM B265-52T, grade 2). Components: 99.2% min Ti; impurities: 0.10% max N; 0.20% max C; 0.25% max Fe; 0.02% max W; 0.25% max O; others (total) 0.25% max; others (each) 0.10% max

Table I. Typical Mechanical Properties of Annealed Titanium Sheet (99.2 Ti) at Elevated Temperatures

Temp, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Per- centage Re- duc- tion in Area	Per- centage Elong- ation in 2 in.	Impact Strength, ft-lb ^(a)
75	78,000	62,000	51	27	45
200	62,000	46,000	57	35	50
400	44,900	29,000	66	39	60
600	34,600	19,000	72	37	68

^(a) Not annealed sheet. Charpy V-notch impact strength at -110°F, about 40 ft-lb

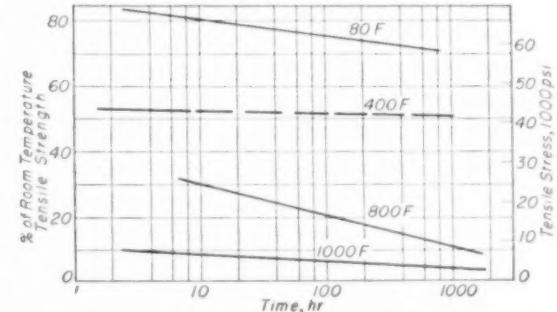


Fig. 2. Stress-Rupture Curves for Annealed Titanium Sheet (99.2 Ti)

Titanium (99.0 Ti)

A 1 Common name. Unalloyed titanium, 70,000 psi design yield strength

3 ASTM number. ASTM B265-52T, grade 3

5 Other designations. AMS 4901 (sheet and strip) and AMS 4921 (bars and forgings)

B 1 Typical uses. Where intermediate strength and good fabrication properties are required

C 1 Density. 4.54 g per cu cm (0.164 lb per cu in.)

D 6 Thermal expansion. Same as 99.2 Ti, above

11 Specific heat.

0 to 120°C (32 to 250°F) 0.129 cal per g

0 to 260°C (32 to 500°F) 0.133 cal per g

0 to 538°C (32 to 1000°F) 0.141 cal per g

16 Thermal conductivity.

-18 to 93°C (0 to 200°F) 10.3 Btu/hr/sq ft/ft/F

-18 to 205°C (0 to 400°F) 10.2 Btu/hr/sq ft/ft/F

-18 to 316°C (0 to 600°F) 10.1 Btu/hr/sq ft/ft/F

E 2 Electrical resistivity at 20°C (68°F). 55 microhm-cm

Table I. Typical Mechanical Properties of Annealed Titanium Sheet (99.0 Ti) at Elevated Temperatures

Temp, deg Fahr	Form	Tensile Strength, psi	Yield Strength, psi	Percentage Reduction in Area	Percentage Elongation in 2 in.	Impact Strength, ft-lb ^(a)	Modulus of Elasticity, psi
75	Bar	95,000	80,000	47	27	18	15,800,000
75	Sheet	95,000	78,000	48	23	..	15,500,000
200	Bar	77,000	61,000	51	22	25	15,000,000
200	Sheet	72,000	57,000	51	25	..	14,500,000
400	Bar	54,000	38,000	54	22	40	13,800,000
400	Sheet	51,000	34,000	56	29	..	13,500,000
600	Bar	43,000	27,000	61	26	55	12,500,000
600	Sheet	41,000	24,000	57	30	..	12,500,000

^(a) Charpy V-notch impact strength at -110°F, about 40 ft-lb

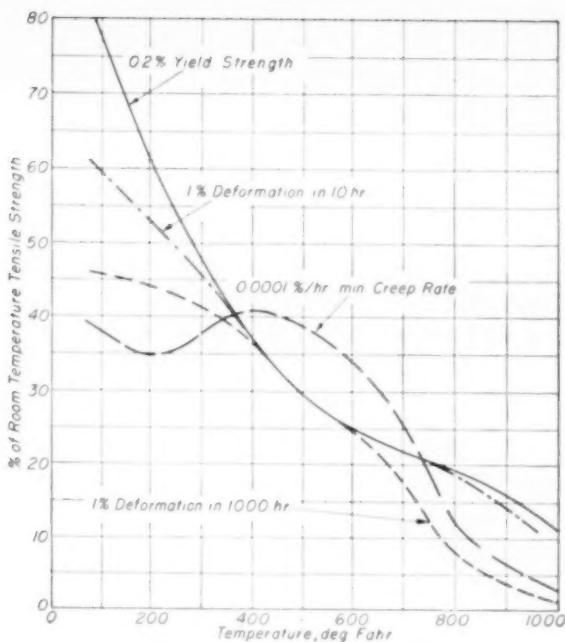


Fig. 1. Creep Properties of Annealed Titanium Sheet (99.0 Ti)

5 Temperature coefficient of electrical resistivity, -18 to 205 C (0 to 400 F). 0.17 per C

I 2 Resistance to specific agents. See page 83.

K Mechanical properties. See Table I.

6 Creep properties. See Fig. 1 and 2.

9 Damping capacity. Log decrement, -0.03%.

M Composition limits (ASTM B265-52T, grade 3). Components: 99.0% min Ti; impurities: 0.15% max N; 0.20% max C; 0.25% max Fe; 0.02% max W; 0.25% max O; others (total) 0.25% max; others (each) 0.10% max

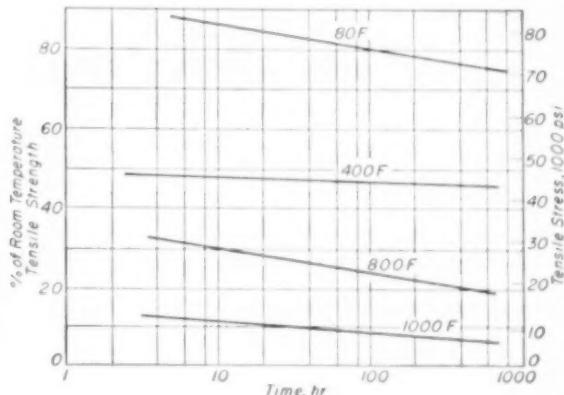


Fig. 2. Stress-Rupture Curves for Annealed Titanium Sheet (99.0 Ti)

Typical Mechanical Properties of Commercial Titanium Alloys at Elevated Temperatures

Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Percentage Elongation in 2 in.	Modulus of Elasticity, psi	Charpy Impact, ft-lb	Stress for 1% Creep in 1000 hr, psi
Ti-8 Mn (AMS 4908)						
75	130,000	120,000	20	15,500,000	18	92,000
200	120,000	100,000	19	14,900,000	27	86,000
400	105,000	77,000	17	13,500,000	45	77,000
600	95,000	67,000	13	12,300,000	64	67,000
800	80,000	52,000	25	11,000,000	75	53,000
Ti-4 Al-4 Mn (AMS 4925)						
75	150,000	135,000	17	16,600,000	18	96,000
200	133,000	120,000	16	15,900,000	21	84,000
400	120,000	105,000	15	14,800,000	37	74,000
600	110,000	93,000	15	13,700,000	59	64,000
800	95,000	77,000	20	12,600,000	70	50,000
Ti-2 Fe-2 Cr-2 Mo						
75	147,000	128,000	22	.....	..	.....
200	131,000	107,000	23	.....	..	.....
400	113,000	88,000	22	.....	..	.....
600	100,000	73,000	19	.....	..	.....
800	80,000	50,000	22	.....	..	.....
Ti-5 Al-1.4 Cr-1.3 Fe-1.3 Mo						
75	150,000	135,000	10	.....	..	.....
200	140,000	128,000	20	.....	..	.....
400	132,000	118,000	20	.....	..	.....
600	106,000	92,000	18	.....	..	.....
Ti-3 Al-5 Cr						
75	150,000	140,000	12	16,500,000	34	.....
200	145,000	135,000	18	.....	49	.....
400	135,000	105,000	20	.....	57	.....
600	115,000	85,000	20	14,100,000	83	.....
800	110,000	75,000	22	14,700,000	84	.....
Ti-5 Al-2.5 Sn						
75	125,000	120,000	18	.....	30	92,000
200	105,000	95,000	19	.....	..	80,000
400	80,000	70,000	17	.....	..	65,000
600	70,000	55,000	17	.....	..	51,000
800	68,000	54,000	16	.....	..	34,000
1000	60,000	50,000	18	.....	..	9,300

DESIGN AND APPLICATION

	PAGE
Engine Metals and Engine Wear	91
Cylinders and liners. Piston rings. Pistons. Camshafts and tappets. Valves, seats and guides. Piston pins. Bushings. Crankshafts. Bearings. Water pump shafts.	
Effect of Stress Concentration on Design Strength	97
Service failures from stress concentration. Definitions and basic concepts. Application to design. Notch sensitivity. Combined steady and alternating stress components. Notch effect for a limited number of cycles. Reducing effects of stress concentration.	
Shot Peening and Other Surface Working Processes	104
Extent of improvement. Residual surface stresses. Shot peening. Quality control. Surface rolling. Roller tools. Hand and mechanical peening. Prestressing.	
Design of Ferrous Castings	109
Design principles. Patterns. Gray iron castings. White iron and chilled iron. Malleable iron castings. Pearlite malleable. Nodular iron. Steel castings.	
Design of Brazed Joints	115
Types of joint. Filler metal and base metal. Joint clearance. Strength of brazed joints. Stress distribution. Fatigue strength. Impact strength. Elevated and sub-zero temperatures. Electrical conductivity. Corrosion resistance. Braze processes.	

Engine Metals and Engine Wear

By the ASM Committee on Engine Metals

IN SUPPLEMENTING the general discussion entitled "Wear of Metals", in the 1948 Metals Handbook, this article shows by specific examples how problems of metal-to-metal wear are solved or compromised in one important type of machine, the internal combustion engine.

These problems are not solved by stress analysis and seldom by laboratory investigation, but by selecting metals for trial, shaping them into experimental or service parts, building the parts into engines and running the engines.

If superior performance of the parts is proved in such limited service, they may be incorporated in production models. In extended service, they would then be subjected to widely varying conditions of lubrication, abrasion, loading and temperature. The metals discussed in this article have shown superiority in the wide range of conditions encountered in general service.

Since wear problems are solved, wholly or in part, by the proper selection of metals, an important feature of this article is the identification of those metals currently in successful use in 14 types of parts that are subject to wear in engines.

An extensive discussion of engine metals would not be justified if it had no application elsewhere. Despite the highly specific character of any wear problem, many aspects of engine wear and engine metals are strongly suggestive of solutions to metal-to-metal wear problems in other machines having parts that rotate or reciprocate under comparable or less severe conditions of load and lubrication.

Terminology

It is generally agreed that engine parts wear by abrasion, scuffing or corrosion. Exact definitions of these terms are more difficult to agree on.

Abrasion, in engines, is caused by airborne dirt, by wear debris from the abraded parts or from other engine parts, or by built-in dirt such as chips and core sand.

Parts abraded by airborne dirt usually show a gray lapped appearance,

because the abrasive dirt is usually very fine, and the worn surfaces are distinguished by a visual matte finish revealing no indication of the direction of motion of the part. Wear from debris of worn parts usually gives a visible scratch pattern, since particle sizes are usually larger than those from airborne dirt. Built-in dirt such as chips and core sand produces much larger scratches in a coarser pattern or as individual traces.

Scuffing is the most rapid form of wear, and is characterized by violent surface disruption from intermittent welding and tearing apart of small areas of the opposing wear surfaces. In the severest form of scuffing, the melting temperature of either or both mating parts may be reached at localized areas, causing the part to wear out in a few minutes. Mild incipient scuffing may appear as small isolated areas

Subdivision	Page
Terminology	91
Service Conditions	91
Cylinders and Liners	91
Piston Rings	93
Pistons	94
Camshafts and Tappets	94
Valves	95
Valve Seats	95
Valve Guides	95
Piston Pins	95
Piston Pin Bushings	96
Crankshafts	96
Bearings	96
Water Pump Shafts	96

which scuff and heal, causing only slightly abnormal wear rates.

Corrosion can be caused by products of combustion or condensation resulting from operation of the engine below its optimum temperature. Engine parts so corroded may be readily identified by their appearance.

Service Conditions

Normally all reciprocating engines operate with lubrication, and this article is confined to lubricated wear. Oil of the wrong viscosity or oil which deteriorates in service will have a decided influence on wear, especially of cylinders, cylinder liners, rings, camshafts and valve gears.

The products of combustion of the fuel contain water vapor which carries potentially corrosive gases such as oxides of sulfur and nitrogen. If allowed to condense on engine parts, these oxides form acids readily and cause excessive corrosive wear. As an example, the relation between percentage of sulfur in the fuel and the wear of piston rings is shown in Fig. 1; cylinder wear is similarly affected.

Corrosive wear is minimized by running the engine hot and by hastening warm-up. The results shown in Fig. 2 are typical in that they show reduced piston ring wear at temperatures above 160°F; wear of cylinders follows the same pattern. Also, lubricant additives will often inhibit corrosive effects, as illustrated in Fig. 3.

Cylinders and Liners

Most of the wear of cylinders and cylinder liners in internal combustion engines occurs in the upper end of the piston travel. It is usually greatest where the top compression ring stops and reverses direction, with a wear pattern corresponding to that shown schematically in Fig. 4. The change in direction causes partial failure of the

Fig. 4. Normal Wear Pattern of Piston Rings Against Cylinder Wall in Gasoline Engines

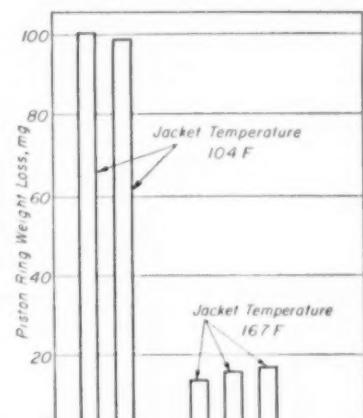


Fig. 2. Effect of Temperature of Jacket Coolant on Wear of Piston Rings (J. T. Burwell, Jr.)

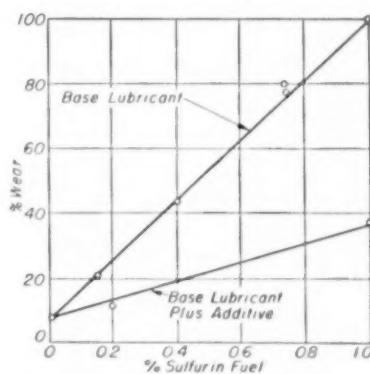


Fig. 3. Effect of Adding Organic Salt to Neutralize Wear and Deposits Caused by Sulfur in Diesel Fuel. Wear expressed as a percentage of wear with base lubricant and fuel having 1% S (J. T. Burwell, Jr.)

Supplements the article entitled "Wear of Metals" on pages 216 to 222 of the 1948 ASM Metals Handbook

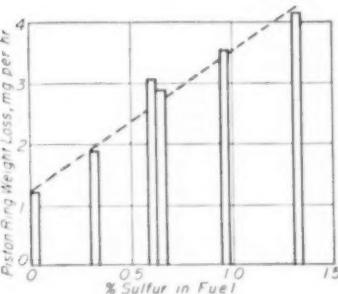


Fig. 1. Relation Between Sulfur Content of Fuel and Wear of Piston Rings in a Diesel Engine (J. T. Burwell, Jr., "Mechanical Wear", American Society for Metals, 1950)

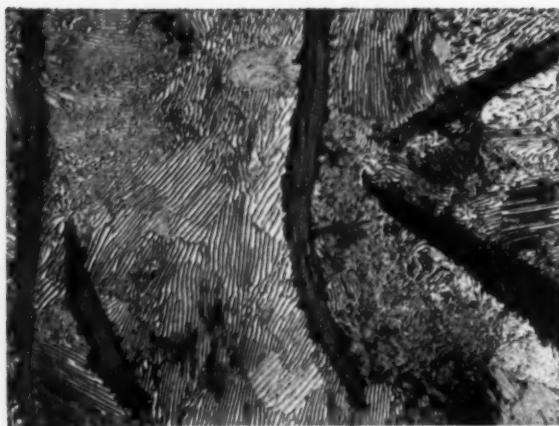


Fig. 5. Typical Structure of Gray Iron for Best Wear Resistance. $\times 500$

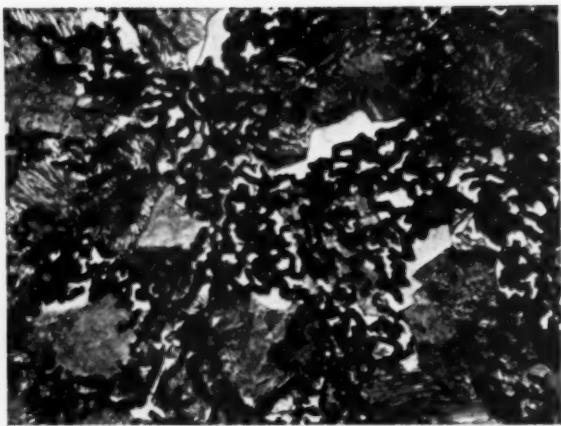


Fig. 6. Type D Structure of Gray Iron That Gives Poor Wear Resistance. $\times 500$

oil film, a condition known as "boundary lubrication".

At the top of piston ring travel, where temperature is greatest and pressure behind the ring is at a maximum, the amount of oil is least. At the lower end of ring travel, wear is increased because, here again, the ring stops momentarily and boundary lubrication results. Large amounts of abrasives in the entering air or oil will change the wear pattern.

Wear of diesel and gas engine cylinders also follows the pattern shown in Fig. 4 for gasoline engines. Similarly, in two-cycle engines, the greatest wear is at the extreme top of the stroke of the top ring, and wear is also increased across the exhaust ports when they become overheated. Hot exhaust ports may cause scuffing; a higher wear rate is inevitable at bridges because of area reduction.

Metals in Use. Cylinder blocks in passenger cars are almost always made of unalloyed gray iron; in heavy-duty trucks use of alloy iron is conventional (Table I).

Gray iron is used for all large engine cylinders or liners, either in the as-cast or stress relieved condition, because of its good frictional qualities and wear resistance, as well as for good machinability and low cost. In general, a ladle-inoculated gray iron with carbon equivalent [total C + $\frac{1}{3}$ (Si + P)] close to eutectic composition [4.3 - $\frac{1}{3}$ (Si + P)] is used for such equipment. The carbon and silicon contents are adjusted

to avoid chilling, and a graphitizing inoculant is usually added.

As is shown in Table I, alloy irons are used extensively, but nickel and molybdenum, added for their graphitizing effects, may also produce free ferrite in the matrix, a condition to be avoided by proper changes in the carbon equivalent. Combinations of nickel, chromium and molybdenum, and sometimes chromium alone, are used with the proper base analysis to give improved wear resistance. A typical composition is 1.25% Ni, 0.35% Cr, and 0.30% Mo added to the base analysis for cylinder liners given in the fourth line of Table I.

Gray iron liners having type A graphite distribution (see 1948 Handbook, Fig. 12 on page 511) with a matrix of 100% pearlite give excellent resistance to mechanical wear. The finer the graphite and pearlite, the better the wear resistance. Figure 5 is typical of a satisfactory structure. Gray iron with type D graphite and free ferrite (Fig. 6) gives poor wear and considerable scuffing.

In automotive diesel engines hardened sleeves are sometimes used, preferably of type A medium graphite structure. Cylinders for high-output military and commercial aircraft engines are generally of nitrided steel or alloy steel similar to 4140. Engines of less than 225 hp for light planes may have gray iron cylinders.

In new assemblies, cylinders may be chromium plated; worn cylinders are

often plated or replated to restore original dimensions.

Cylinders were chromium plated during the last war, for both submarine and aircraft engines; postwar commercial applications are in diesel electric locomotive engines, marine engines and heavy-duty automotive diesels, as well as in small air-cooled aluminum cylinders. Most chromium plated cylinder surfaces consist of some form of interrupted surface, generally porous chromium. An interrupted surface may be obtained by electrolytic or chemical etching of chromium after it is plated on a smoothly honed bore, as with porous chromium, or by pre-roughening the bore by shot blasting, knurling or tooling and then reproducing these rough features in the final chromium plate.

Two distinct types of porous chromium are produced. One has pin-point porosity (Fig. 7) with many microscopic depressions in a honed chromium surface. This has been used in all types of engine cylinders except aircraft. Channel porosity (Fig. 8) is used for aircraft. This surface is also finish honed but is broken by random connected channels leaving isolated bearing plateaus.

For both types, the percentage "porosity" is generally controlled between 20 and 50% of the total area. Average plateau size is further controlled between 0.010 and 0.030 in. diam with the channel type of porosity. Porosity as low as 5% approaches dense chromium

Table I. Metals for Engine Parts

Service	C	Si	Mn	Composition Ranges, %				Cr	Other	Brinell Hardness Number
				P	S (max)	Ni				
Cast Iron Cylinder Blocks										
Passenger car	3.10 to 3.50	1.90 to 2.30	0.60 to 0.90	0.12 to 0.18	0.125	0.10 ^(a)	0.20 ^(a)	.....	.....	163 to 228 ^(d)
Trucks	3.00 to 3.50	2.20 to 2.50	0.50 to 0.70	0.20 max	0.10	0.35 to 0.45	0.25 to 0.50	0.70 to 0.80 Mo	.....	217 to 241 ^(e)
Cast Iron Cylinder Liners										
Auto diesel	3.25 to 3.50	2.00 to 2.25	0.50 to 0.80	0.25 max	0.12	.....	0.30 to 0.50	1.00 to 1.50 Cu	420 to 485 ^(d)	.....
Diesel & gas	2.85 to 3.30	1.25 to 1.75	0.60 max	0.20 max	0.12	1.00 to 1.50 ^(e)	0.30 to 0.40 ^(e)	0.25 to 0.35 Mo ^(e)	.....	180 to 250
Cast Aluminum Alloy Pistons (Alloy D132)										
Automotive	8.5 to 10.5	.....	.....	.....	0.5 to 1.5	0.7 to 1.3 Mg	2.0 to 4.0 Cu	90 to 130	.....	.....
Cast Iron Piston Rings (AMS 7310B)										
All types	3.50 to 3.90	2.20 to 3.10	0.40 to 0.80	0.30 to 0.80	0.10	.....	.....	.....	.....	222 to 267 ^(f)
(a) Optional elements. (b) 35,000 psi tensile strength, 2,400 lb transverse breaking load in 18 in.; see page 125, 1948 Metals Handbook. (c) 2,700 lb transverse breaking load in 18 in. (d) Specified value is Rockwell B 97 to 104.										
Quenched from 1575 F to 475 F salt bath, tempered 1 hr at 400 F. (e) May be added to improve wear resistance. (f) Specified value is Rockwell B 97 to 104.										

and is susceptible to scoring because of sparse oil distribution. High porosity, such as 75%, may cause high initial ring wear and high oil consumption. In normal engine service, cylinders plated with chromium of optimum porosity give wear rates $\frac{1}{3}$ to $\frac{1}{10}$ those of uncoated cast iron or steel, hardened or unhardened.

Wear of steel cylinders in aircraft engines may be of the normal type in airline service or of the corrosive type in military service. Engines of military and private airplanes deteriorate mainly by cylinder corrosion during storage, resulting in rapid cylinder wear and early overhaul because of high consumption of lubricating oil. Still longer storage results in pitted bores, which is the principal reason why the Armed Forces usually chromium plate worn cylinders.

Hardness is an important factor in wear resistance. Gray iron, as cast, gives good wear resistance at 180 to 250 Brinell. Hardening increases resistance to abrasive wear, especially in high-speed and high-load applications. Nitrided surfaces harder than 600 Brinell can be used. Rockwell or other small diamond-point hardness impressions on cast iron may be misleadingly low because the soft graphite flakes in the structure are of the same order of size as the hardness indenter.

Finish on cylinders is usually 15 to 35 micro-in. in automotive, diesel and aircraft engines. Smoother finishes retard proper seating of the rings. On the other hand, coarse finish will accelerate initial wear and oil consumption and may accelerate wear throughout the life of the barrels.

It is well known that gray iron cylinders which wear well, "break in" to a glazed surface. Lack of this type of surface is a good indication of high wear. A glazed surface cannot be obtained artificially, but only by operating the engine. This early break-in period is crucial, and is influenced greatly by surface finish. A highly burnished or polished surface will scuff or gall, while a dull honed finish will usually perform satisfactorily. Various turned and ground finishes have been used, but these are slow to break in, causing excessive oil consumption.

Break-in may be influenced by heavy machining cuts which tend to force metal into the spaces occupied by graphite flakes. Such metal particles

are difficult to remove by subsequent honing and begin scratching with the first stroke of the piston, producing a surface which appears to be disintegrating. The particles can be removed by the light etching of a phosphate treatment.

Cylinder barrels are sometimes phosphate-coated to give anti-welding characteristics and to reduce scoring and galling. Such a surface holds thin oil films tenaciously.

An efficient air cleaner is very important because airborne dust causes serious wear of cylinders.

Piston Rings

The principal factors that influence wear of piston rings are speed, temperature, load, frequency of use and dirt.

Speed influences ring wear largely as a function of piston travel per mile. The rate of ring wear in a high-speed engine of a given power rating is higher than that of a low-speed engine of the same rating in proportion to the distance traveled by the rings. Design weaknesses of rings, pistons and cylinders become more evident as speed increases.

While radial face wear is the prime consideration, wear of ring and groove sides cannot be ignored. Engine speed affects wear of these side surfaces because it affects the acceleration forces on the rings.

Temperature has a most important effect. While high temperature occasionally causes wear by interfering with lubrication of cylinder surfaces, low temperature is a far more frequent source of excessive piston and ring wear. As coolant temperature falls below 160°F, cylinder and ring wear increase rapidly because of corrosion by condensate carrying corrosive products of combustion. Where it is impossible to maintain proper temperatures, additive types of lubricating oil are helpful.

Engine Load affects the wear rates of both cylinders and rings principally through its influence on temperatures and corrosive wear. Engines in light-load service usually have a high rate of corrosive wear. If temperatures are optimum, wear is usually less in light-load than in high-load applications. High loads seldom cause wear problems unless design weaknesses cause scuff-

ing because of distortion or destruction of the oil film by hot spots.

Frequency of Use is one of the most important influences. Engines operated the most miles per year have the lowest rates of cylinder and ring wear. On the other hand, low annual mileage usually means short runs, more starts per mile and detrimentally low operating temperatures; the sensitivity of an engine to this type of wear is largely determined by its warm-up rate.

Airborne Dirt is a chronic cause of excessive ring wear. Proper maintenance and design of filter equipment is essential to avoid it. Prevention of air leaks between filters and engine is also imperative. Dirt in the lubricating oil is a less frequent problem but design and maintenance of oil filters and seals is a vital consideration.

Ring Metals. Gray cast iron is the most widely used metal for compression and oil rings of all types. A representative specification is AMS 7310B (Table D). It has the best bearing quality of all the basic types and is universally used in compression rings which are not chromium plated.

A variety of materials is used for compression rings requiring high strength. These start at a minimum tensile strength of 65,000 psi for statically-cast iron, and range to about 90,000 psi for centrifugally-cast iron. There are no SAE specifications for these materials. 1070 and 52100 steels are also used.

Iron or steel of high strength is usually chromium plated. Because the fatigue limit of steel or cast iron is considerably reduced by plating, it is often necessary to specify high-strength varieties.

Chromium plate itself is a ring material, as it is used in sufficient thickness, usually 0.005 in., to last the life of the ring. Reduction in wear rate through the use of chromium plating amounts to about 75% for both rings and cylinders, but chromium plate cannot be run against itself. Chromium plating is widely used in compression rings of all types, in oil rings of the steel-segment type, and is beginning to be used in the conventional ventilated type of cast iron oil rings. It has been adopted for lighter service in passenger cars, heavy-duty diesel engines and natural gas engines.

The steel-segment or steel-rail types of oil rings are almost always made of

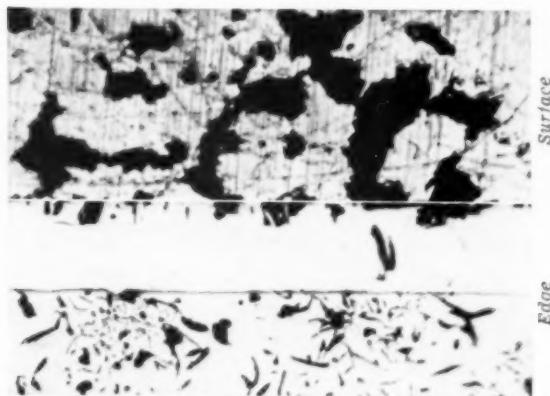


Fig. 7. Surface and Edge of Porous Chromium Plating on Gray Iron. Pin-point type of porosity after honing. $\times 100$



Fig. 8. Surface and Edge of Porous Chromium Plating on Steel. Channel type of coaling after honing. $\times 100$

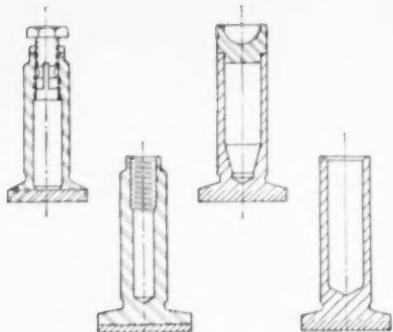


Fig. 9. Mushroom Type of Tappet

1070 to 1095 steel, and are either chromium plated or unplated.

Finish on piston rings depends on the type of ring and the requirements for accuracy, scuff resistance and run-in. Thread finishes varying from 0.0001 to 0.002 in. deep are used on both chromium plated and unplated iron rings. Deep threads give greatest scuff resistance and most rapid development of full bearing; shallow ones give best initial oil economy.

Chromium plated rings are usually lapped or plated so as to be porous on the surface and thus prevent excessive wear-in time and improve scuff resistance. This is true of either smooth or thread finishes. Unplated iron rings are lapped for some applications requiring high initial accuracy.

Surface Treatments to prevent scuffing during run-in may be metallic or nonmetallic. The metallic types have high scuff resistance or low melting points that enable them to flow off high spots. The nonmetallic materials alleviate scuffing by serving as contaminants that prevent surface welding. Metallic coatings in current use are tin and cadmium. Nonmetallic coatings are iron oxide (Fe_2O_3), phosphates or sulfides, all supplied under various proprietary names.

Pistons

All passenger car engines now have aluminum alloy pistons because of their low weight (inertia) and high thermal conductivity. Aluminum has the disadvantage of high embeddability (ability to embed dirt), which is an important cause of wear in abrasive climates. The grooves are sometimes nickel plated, or cast inserts are used. Immersion tin plating or anodizing is common, to reduce break-in and wear of aluminum alloy pistons. The aluminum alloy most used is D132, whose composition is shown in Table I.

Pistons in other types of engines are made of aluminum, gray iron or malleable iron of various compositions and hardnesses.

Camshafts and Tappets

The tappet is a member sliding in a guide, interposed between the cam-shaft and the push rod in overhead valve engines, or between the camshaft and valve stem in L-head engines. Both the mushroom tappet shown in Fig. 9 and the barrel type shown in Fig. 10 are used extensively in mechanically adjusted tappets and hydraulic lifters.

Combinations of camshaft and tappet metals in common use are:

- 1 **Cast iron camshaft and hardened steel tappet.** Where surface stresses are low, this combination will be the least expensive. A hardened cast iron cam-shaft may fail rapidly if the tappet face is roughened by spalling or seizure.
- 2 **Steel camshaft and chilled iron tappet.** A steel camshaft will generally survive contact with a damaged tappet face. The use of chilled iron for the tappet would be dictated by relatively high loads.
- 3 **Cast iron camshaft and chilled iron tappets** have also been used for many years.
- 4 **Cast iron camshaft and hardened gray iron tappets** are a relatively new combination.

Camshaft Metals. Hardenable gray iron camshafts are the most widely used. One popular grade is a Cr-Ni-Mo iron with total carbon about 2.00% and enough combined carbon (0.60 to 1.2%) to give Rockwell C 45 to 50 on the surfaces after hardening. Iron cast with a controlled chill may be used without subsequent hardening.

Steels may be water-quenched carbon steels, oil-quenched alloy steels of 0.50 to 0.70% C, or a carburizing grade. Heat treatment is either conventional through hardening, or selective flame or induction hardening.

Tappet Face Materials. Steel tappets are either hardened, or carburized and hardened. If uncarburized, they are usually 52100 or high-carbon molybde-

num steels of the 4000 series; carburized tappets are most often made from alloy steels such as 5120. Steel tappets fail by scuffing or rapid loss of surface.

Cast iron for tappets is usually one of four types:

- 1 **Chilled cast iron**, with or without alloying elements for chill control and body strength, permits the highest loads of any metal against a steel cam-shaft. Its mode of failure is generally by fatigue, pitting or spalling and only rarely by scuffing or wear. The pitting tendency may be increased by some lubricant additives. Chilled iron tappets run well against both steel and hardened cast iron camshafts.
- 2 **Hardenable gray iron** is relatively new and is similar to that used for cam-shafts. Lubricant additives improve its resistance to wear and scuffing. Failure is by scuffing and rapid loss of surface. For successful operation, hardenable gray iron requires extremely close control of graphite size and dispersion, combined carbon content and dispersion, and heat treatment.
- 3 **Puddled chilled iron** on a steel backing has the advantage of the wear resistance of chilled iron combined with the high strength of a steel body. This combination is obtained by melting a disk of cast iron on the steel face, by means of an open d-c arc and a carbon electrode.
- 4 **Mottled hardenable cast iron** is intermediate between chilled iron and hardenable gray iron. It is cast with a hypereutectoid content of combined carbon (often 1.5 to 2.0%) and is subsequently hardened by quenching from 1550 F.

Finishes. Tappet faces are usually finished to about 6 micro-in. In a few applications, shot peened steel tappet faces seem to retain lubricant slightly better. Oxide coating of superfinished tappet faces on chilled iron or phosphate coating of hardened steel or gray iron, improves frictional qualities and accelerates wearing-in. The superfinished surface is slightly roughened by this treatment. Cam surfaces are usually slightly rougher than the tappet surface, and are sometimes phosphated for the same reasons as tappets. Polishing a cam surface that is too rough after grinding may mean the difference between success and failure of a cam-tappet combination.

Design. Contact stress is at a minimum with perfect alignment as shown in Fig. 11(a). Misalignment and de-

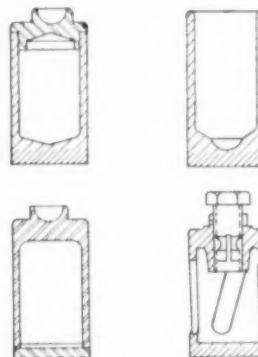


Fig. 10. Barrel Type of Tappet

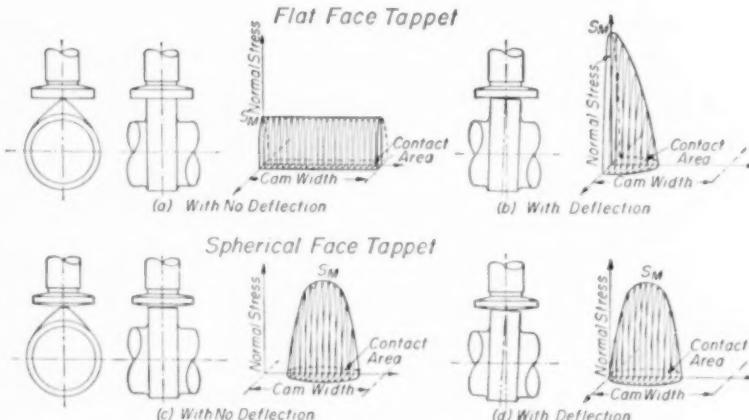


Fig. 11. Effect of Contact Pattern on the Stress on Tappet Face

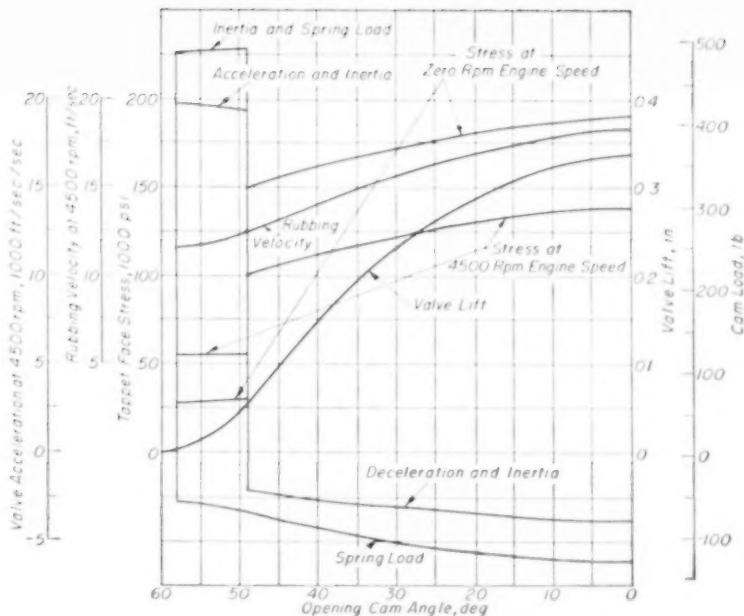


Fig. 12. Stress on Tappet Face Versus Cam Angle

flections can result in an extremely high stress in a small area of the flat tappet face during operation, as indicated by Fig. 11(b).

Figure 12 shows theoretical curves for stress versus cam angle for chilled iron tappets and steel cams. Similar relations can be worked out for other combinations, but are valid only when conditions at the area of contact are under control.

A spherical tappet face of 30 to 60-in. radius, as illustrated in Fig. 11(c) and 11(d), avoids the high stresses of outright misalignment, but stresses exceed those accompanying true alignment and flat faces. A recent design solution to the misalignment problem, when stresses are too high for a spherical face to be used, is shown in Fig. 13.

Valves

An exhaust or intake valve is made of a single steel, rather than a composite, wherever possible, to reduce the cost of manufacture. For intake valves, and for exhaust valves up to about 1000 F, alloy steel 3140 is in general use. Steels 5150, 8440 and others have been used as alternates.

To reduce wear of the valve face by scaling, the stem may be of low-alloy steel welded to a head of more heat-resistant alloy. Table II, on page 563 of the 1948 Metals Handbook, lists 21 heat-resistant steels used for exhaust valves, and the notes in the table explain the principal differences in application among the different types.

Hot dip aluminum coating of exhaust valves made of highly alloyed steel can double service life. When austenitic steels are required for high-temperature strength and reduction of wear, it is frequently necessary to weld on a hardenable stem, to reduce scoring and scuffing in the valve guides.

The stem is usually ground to a 12 to 40-micro-in. finish; rougher surfaces

are sometimes preferred as an aid in lubrication; shot peening increases surface roughness and hardness for improved wear resistance. Under exceptional conditions, stems are chrome plated.

In certain engines, corrosion of the valve stems by hydrobromic acid from the fuel can be prevented by using a 13% Cr stainless steel stem, welded to an austenitic head.

Tip hardness of Rockwell C 38 to 41 is satisfactory for moderate duty; for greater wear resistance the maximum is Rockwell C 50. When tip wear is more severe, a separate hardened tip of steel such as 52100, hardened to Rockwell C 60, can be used.

Valve Seats

The lowest-cost seats are produced by finishing the soft cast iron of the cylinder block or cylinder head. When a nonleaded fuel is used, valve seats must be more carefully considered because tetraethyl lead in gasoline deposits a protective coating of lead salts on valve seats and valve faces. When a soft cast iron seat is not suitable, a separate insert of hardened cast iron is the next best selection. Weld deposits or castings of cobalt-base or other hard-facing alloy are used for still greater wear resistance. A high-alloy valve and a cast cobalt-chromium-base alloy seat-insert represent an exceptionally good combination. Thermal expansion of alloy seats must be similar to the holder material.

At best, exhaust valve seats may wear rapidly in heavy-duty engines. Devices to rotate the valve are available and help reduce wear.

Valve Guides

Valve guides are usually made from pearlitic gray iron having no free ferrite. Improved wear is obtained by coating the guides to produce an iron

oxide or phosphate coating, both of which etch the surface to develop pits for lubricant and add a nonmetallic layer that reduces scuffing and rubbing wear.

Bronze guides serve in exceptional circumstances where much heat is removed through the valve stem, as in sodium-cooled valves. A common material is SAE 701C, a high-strength aluminum bronze of good corrosion resistance and low coefficient of friction against steel.

Lubrication is improved by reaming valve guides to provide shallow grooves to retain the oil. A broached surface is too smooth for oil retention.

Piston Pins

The wear of automotive piston pins is readily controlled by proper design, lubrication, steel selection and heat treatment. Other engine parts usually wear out first. Pin wear of 0.001 to 0.002 in. makes a noisy engine but resultant failure is almost unknown. Because of thin oil films and boundary lubrication, pins are finished to 4 to 8 micro-in. to reduce wear. No matter how carefully piston pins are ground, a thin layer of metal should be lapped off, to insure freedom from scuffing and to prevent early increase of dimensional clearance between piston pin and bushing.

For designs requiring improved lubrication or special bearing materials to resist unusual loads, the piston pin may be roughened by grit blasting before grinding, to create small pits in the surface for retaining lubricant.

Steels. Piston pins are made of 1117, 1016 or 5115, carburized 0.030 to 0.040 in. deep and hardened to Rockwell C 60. This hardness must be retained on the final surface.

Piston pins are occasionally worn by corrosive attack by water or condensate in the lubricant. Chromium plating has been used to reduce the attack, but it is better to raise the oil temperature enough to evaporate the water.

Design for Least Wear. The outside diameter of the piston pin is normally about $\frac{1}{4}$ to $\frac{1}{3}$ of the piston diameter, and the bearing widths in the piston and connecting rod are made as long as possible to provide maximum bearing area. A straight hole for the full length of the pin, rather than holes tapered at the ends, as formerly, together with sufficient wall thickness, gives maximum stiffness to prevent out-of-roundness and thereby insures the most uniform bearing load.

The two designs for the small end of connecting-rods—the full-floating pin and pin fixed in the rod to increase bearing area in the pistons—both show acceptable wear in tests and service. For the high compressive loads of diesel engines, the small end of the connecting rod may be tapered, with the narrowest part at the top so that the compressive areas of both the rod and piston bearing are elongated.

Oil must always be available at the

Table II. Bearing and Bushing Bronzes

Similar Specifications	SAE	ASTM	Common Name	Nominal Composition, %						Remarks
				Cu	Sn	Pb	Fe	Zn or P	Al	
Cast Bronzes										
68B	B148-52, 9B	....	Aluminum bronze	88	....	....	1.5	....	10.5	High load, very low speed, excellent corrosion resistance
65	B139-52, D	....	Phosphor bronze	89	11	....	....	0.25 P	....	Heavy load, low speed
64	B144-52, 3A	....	High-leaded tin bronze	80	10	10	....	....	....	Heavy load, moderate speed
660	B144-52, 3B	....	High-leaded tin bronze	83	7	7	....	3 Zn	....	Medium load, medium speed, general use
67	B144-52, 3D	....	High-leaded tin bronze	78	6	16	....	....	....	Medium load, high speed
Wrought Bronzes										
795	.....	....	Bronze	90	0.5	....	....	9.5 Zn	....	Heavy load, low speed
791	B139-52, B2	....	Phosphor bronze	88	4.0	4.0	....	4.0 Zn	....	Medium requirements

bushings. Frequently, the lubricant is fed through a hole in the connecting rod, from the crankshaft to the bearing. Many successful designs have one or more holes in the small end of the rod to obtain oil from the general splashing within the engine case. Grooves which run the length of the bearing areas and take oil from the oil-scraping rings or the splashing lubricant are frequently used.

Oil grooves and holes should be located only after the areas of minimum loading have been properly determined in each design, to allow for dynamic oil films and to decrease wear. An exception to this rule is found in piston pins for two-cycle diesel engines, where loads do not reverse and prevent generation of dynamic oil films. An excellent solution has been to space axial oil grooves equal to the distance traveled by the surface of the pin during each revolution of the engine. This exposes the entire surface of the piston pin to a groove for relubrication during each engine revolution.

Piston Pin Bushings

Piston-pin bushings are usually of bronze or, in heavy-duty applications, of silver. The use of steel-backed bronze bushings is increasing because of their lower cost and greater tightness in the hole. Most piston pin bushings are made from rolled bronze such as SAE 791; cast bushings are also used. In general, more lead and less tin and zinc will improve anti-friction qualities, whereas increased tin content will improve strength and wear resistance. Table II lists popular bronzes, both cast and wrought. Commercial variations of these have additions of phosphorus and nickel to improve soundness and wear resistance.

Corrosion of the bushing by the lubricant is of two varieties. First, acids formed in the lubricating oil by oxidation may preferentially corrode different elements in the bronze. Certain acidic oils will dissolve the lead, whereas other unsuitable lubricants will attack the copper in SAE 60 or 67 bronzes. Aluminum bronze SAE 68B has been used to minimize such corrosive wear.

A second type of corrosion is the attack of copper or silver by active sulfur in the lubricant, forming a sulfide which is then rubbed off. Both these conditions can be corrected by use of the proper oil and reduced oil temperature.

Crankshafts

Wear of crankshafts is caused primarily by foreign matter in the lubricating oil. Cleaning of the engine casting before assembly and the intake air during operation are as important as selection of the journal steel. The best solution is to use a full-flow oil filter that will remove particles (down to 25 microns or less) of sand and other abrasive matter.

Crankshafts are usually made of hardenable steel, such as 1045 at about 250 Brinell. Nodular iron or other cast alloys, when used, are also specified to about the same hardness. Hardening of bearing surfaces is usually done by induction heating. This reduces wear on the bearing, apparently because very hard particles cannot so readily embed in the shaft and wear the soft bearing metal.

Bearings

Bearing materials are selected for anti-score characteristics, fatigue resistance, corrosion resistance and wear, as described in the article "Bearing Materials", page 745 of the 1948 Metals Handbook. Because dirt cannot always

be eliminated, wear may be reduced by the use of the tin or lead babbitts, in which the dirt particles may embed to be kept out of circulation. The commonest type of engine bearing is either lead or tin babbitt on a steel back. Very thin layers (0.001 to 0.002 in.) give long life on bearings of normal size. For larger bearings, 0.005 to 0.008 in. of babbitt is better. Many of these larger bearings have cast iron backs.

A stronger bearing material is frequently needed, such as copper-lead or silver. Both will have high wear rates if the oil is not clean, and silver should not be used where hard particles like sand may be present. The most effective compromise is to use a very thin layer of lead babbitt (for embeddability) over a fatigue-resistant material, such as copper-lead or an aluminum alloy. An overlay as thin as 0.0005 in. will reduce journal wear caused by operation of the engine in dirty air. Small changes in composition of the overlay are not important.

Bearings of the steel-backed copper-nickel-matrix type are used extensively also.

Abrasive wear of journals is reduced by a circumferential oil groove, probably because many of the dirt particles can escape through the unloaded side of the bearing. On the other hand, an axial groove not continued to the edge of the bearing may increase the rate of journal wear.

Water Pump Shafts

Wear in water pump shafts is a good example of a problem eliminated by "designing around it". Formerly, water pump design usually combined the seal and bearing in which wear occurred by a combination of abrasion and corrosion, because the shaft, usually of carbon steel, and the bearing ran in a mixture of lubricant and coolant, resulting in rapid wear. Several new designs had only partial success. Free-cutting stainless steel 416F alleviated the problem prior to wartime allocations, at which time carbon steel shafts with 0.002 in. of hard chromium plate were substituted.

In present design, a shaft of 1117 steel, carburized and hardened, is rotated on double-row ball bearings, packed with grease and sealed for lifetime lubrication, and separate seals keep the coolant away from the bearings. This design has diminished shaft wear to the point where it is no longer a problem.

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Effect of Stress Concentration on Design Strength

By the ASM Committee on Stress Concentration

THE STRESS DISTRIBUTION in a machine part is usually complex. Localized high stresses occur at any sudden change of section, such as at fillets, threads, keyways and grooves. This localization of high stresses caused by the shape of the member is called "stress concentration". The effects of stress concentration are of vital concern to engineers and designers.

This article describes a method for analyzing design and metal jointly to produce a component to withstand service stresses.

Failures in high-duty machines are often caused by fatigue and are nearly always influenced by stress concentration.¹ (Fig. 1 and 2.) In a recent aircraft manual² over 50 failures originating in regions of stress concentration are cited; most are fatigue failures (Fig. 3). A Bureau of Aeronautics pub-

lication (Navair Sm-32) states, "Such (fatigue) difficulties are almost always traceable to improper design, fabrication, and maintenance . . . By studying stress concentration factors much can be learned about how to produce designs that are superior from the standpoint of resistance to repeated loads . . ."

The effect of stress concentration is strikingly illustrated in Fig. 4, page 100; note that each tool has stamped numbers "617" and that each crack starts at a number "1" in the tool.³

Although repeated loading is the most important condition where stress concentration is damaging, there are also instances of static and impact loading where metal behaves in a brittle manner. Multi-axial stress limits deformation and increases danger from stress concentration. Under creep-rupture conditions at high temperature, a

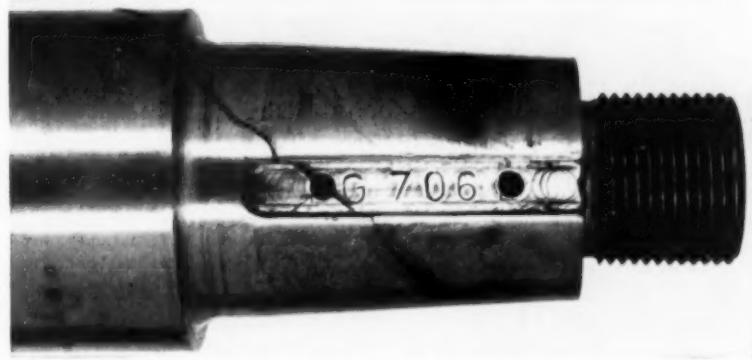


Fig. 1. Torsional Fatigue Crack in a Machine Shaft

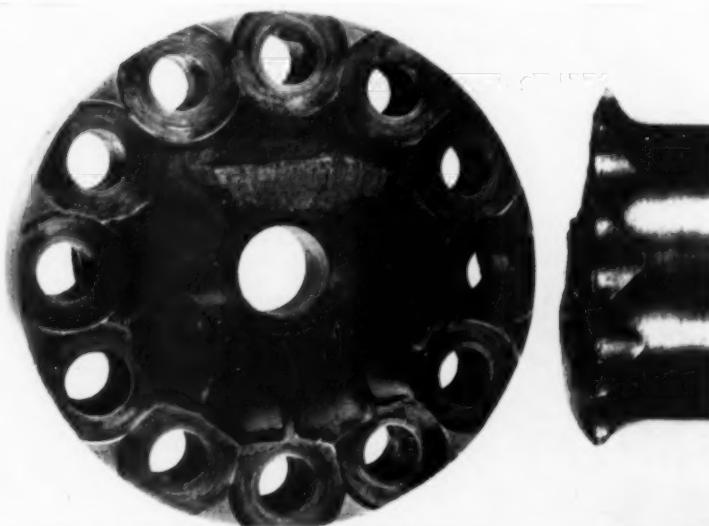


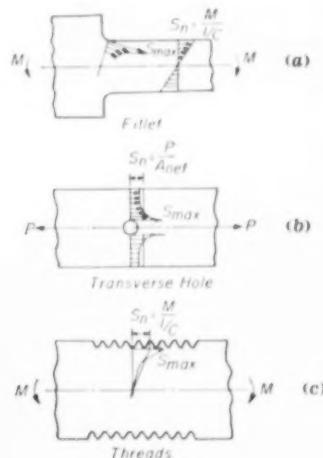
Fig. 2. Fracture of Solid Coupling at Sharp Recesses for Bolt Heads

notch can be quite damaging and allowance must be made in design. Ship hull failures have occurred in a brittle manner, usually at low temperature; one of the main improvements has been rounding of the hatch corners to alleviate stress concentration.

Definitions and Basic Concepts

The definitions used here are from the ASTM Manual on Fatigue Testing.⁴

Nominal Stress, S_n or τ_n , is the stress computed by use of a simple basic formula, omitting stress concentration. For tension, $S_n = P/A$ where P = load and A = net area (see (b) in cut below). For bending, $S_n = M/(I/c)$, where M = bending moment and I/c = section modulus (see (a) and (c) in cut below). For torsion, $\tau_n = T/(J/c)$, where T = torque and J/c = section modulus in torsion.

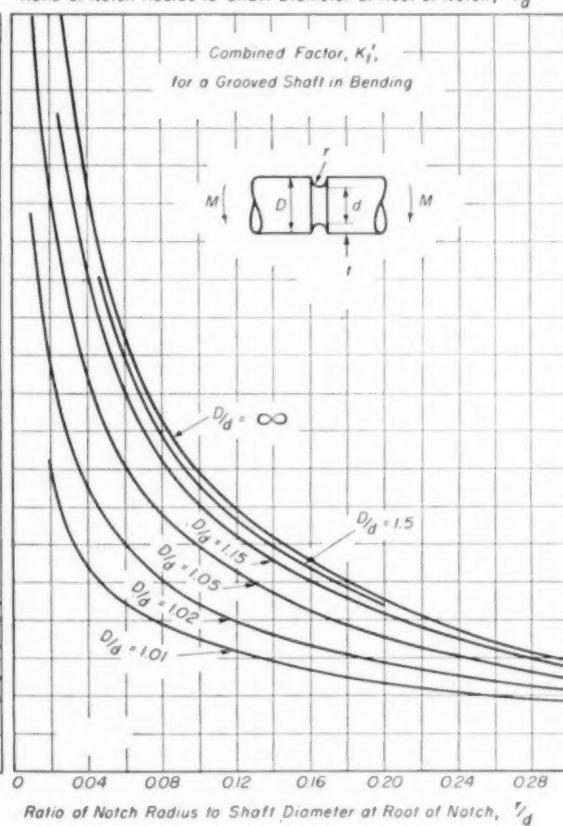
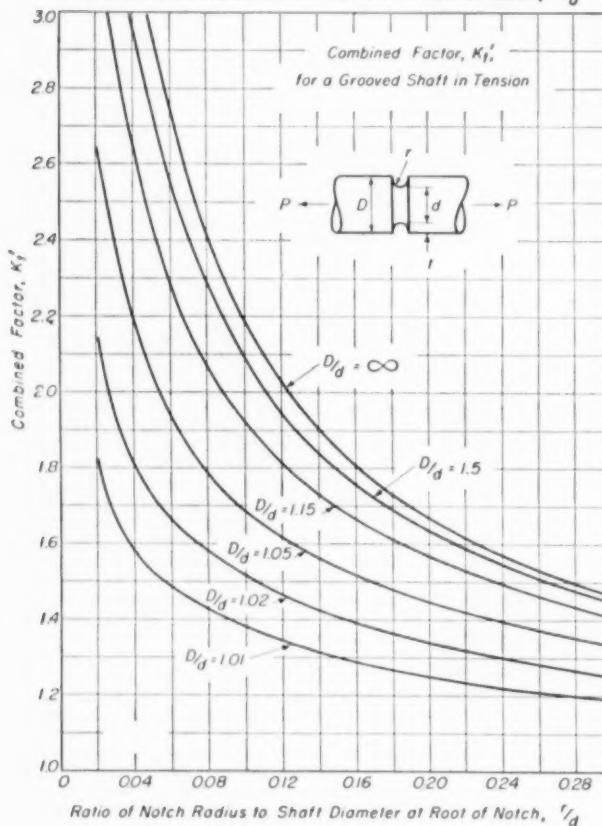
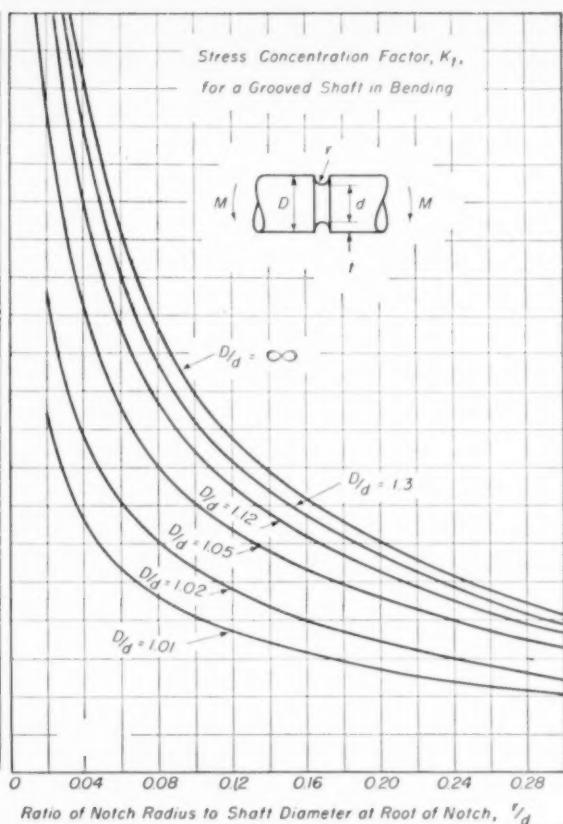
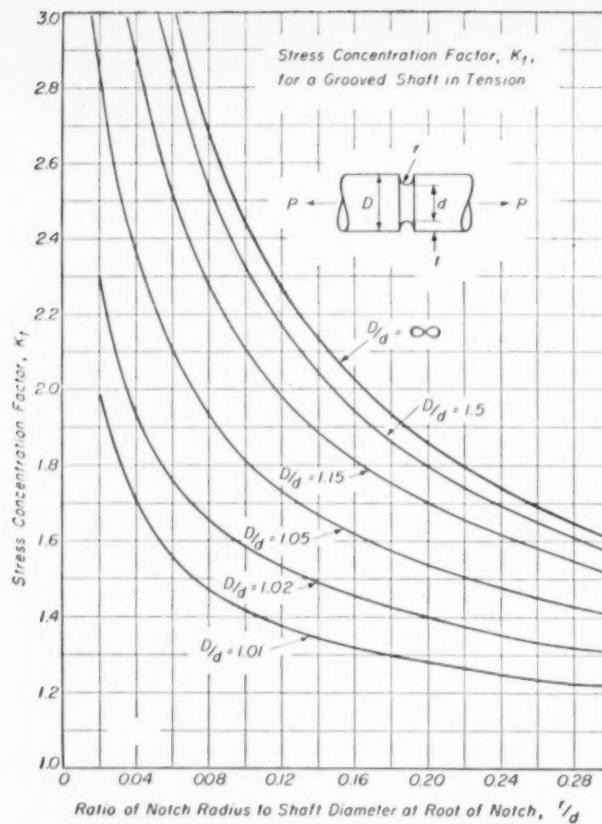


Stress Concentration Factor, K_t , is the maximum stress existing at a region under study divided by the nominal stress.⁵

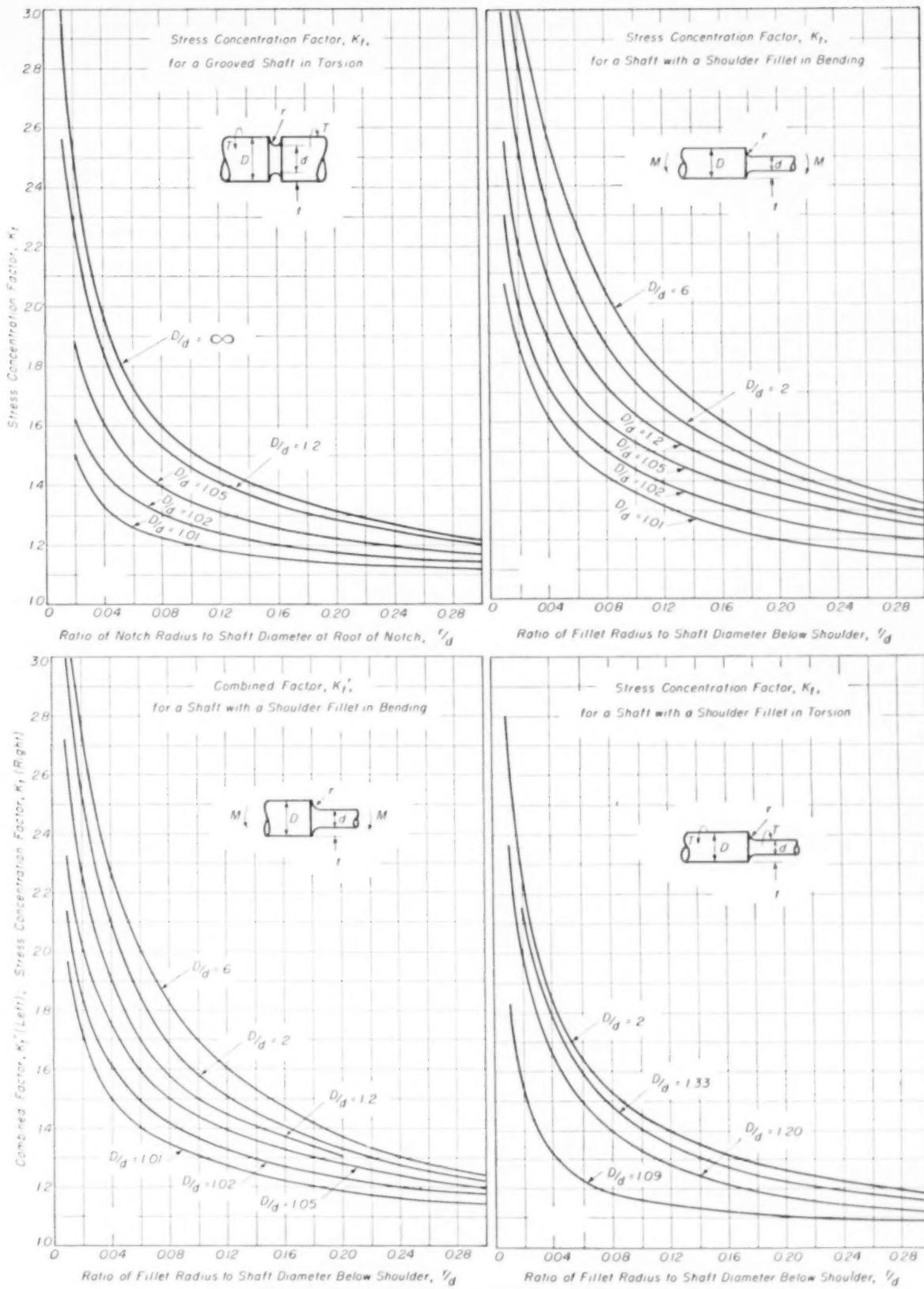
$$K_t = \frac{S_{max}}{S_n}; \text{ and for torsion } \frac{\tau_{max}}{\tau_n}.$$

Stress concentration factors, K_t , are theoretical factors based on the usual assumptions of the theory of elasticity (Hooke's Law, homogeneous and isotropic material). For certain simple shapes, mathematical solutions are available; photoelastic tests on transparent models agree with these solutions, and stress concentration factors have also been obtained by this means for many parts or structures too complicated for mathematical solution. Methods of analogy have also been used for determination of stress concentration factors. For bars of various cross section subjected to torsion loading, the soap film analogy method⁶ and the electrical analogy method⁷ have been successfully utilized. Charts of K_t values are given on the next two pages and in Fig. 5 and 6.⁸

Supplements the section on Design Factors in the article on Service Failures, pages 243 to 245 of the 1948 ASM Metals Handbook



Stress Concentration Factors and Combined Factors for Several Design Conditions



Stress Concentration Factors and Combined Factors for Several Design Conditions

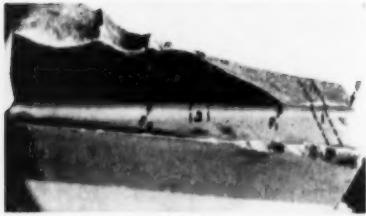


Fig. 3. Fatigue Failure of Airplane Wing Spar. Top—Fatigue fractures at F; tensile fracture area at T. Bottom—Another view; crack f to f₁ to f₂ is fatigue; tensile fracture followed fatigue fracture from f to f₁, but thence through bolt hole.

The Combined Factor, K_t' , is a theoretical factor¹ taking account of stress concentration and the Mises criterion of failure for ductile metals.

$$K_t' = K_t \sqrt{1 - c + c^2}$$

where $c = S_t/S_n$, the ratio of principal stresses at the location of failure ($S_t < S_n$).

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On pages 98 and 99 are given K_t' factors for various basic configurations of design interest.² Since $K_t' = K_t$ for uni-axial stress, as can be seen from the above equation (S_t and $c = 0$), K_t should be used for sheets where t/r is small (t = sheet thickness, r = notch radius). For torsion also, $K_t' = K_t$.

Fatigue Notch Factor, K_f , is determined by fatigue tests only.

$$K_f = \frac{S_f}{S_{nf}}$$

where S_f = fatigue limit or fatigue strength at a specified number of cycles, for an unnotched specimen, and

S_{nf} = fatigue limit or fatigue strength at the same specified number of cycles, for a notched specimen.

Notch Sensitivity, q , represents the degree to which the theoretical effect is actually obtained, and is defined as

$$q = \frac{K_f - 1}{K_t - 1}, \text{ or } \frac{K_f - 1}{K_t' - 1}.$$

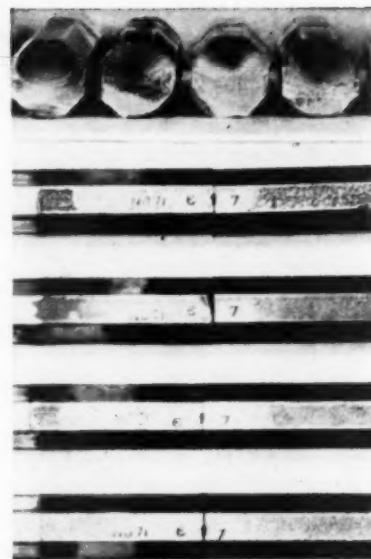


Fig. 4. Fatigue Failure of Chisels. All of these chisels fractured in fatigue at the point of stress concentration caused by the stamped-in numeral 1 in the identifying number 617 on each chisel.

Application to Design

Brittle Metals. As the distinction between brittle and ductile metals is usually indefinite, an arbitrary dividing line is often taken — sometimes 5% elongation in a standard tension test, sometimes lower (for example, 1%). The effects of temperature, high or low, and state of stress are often such

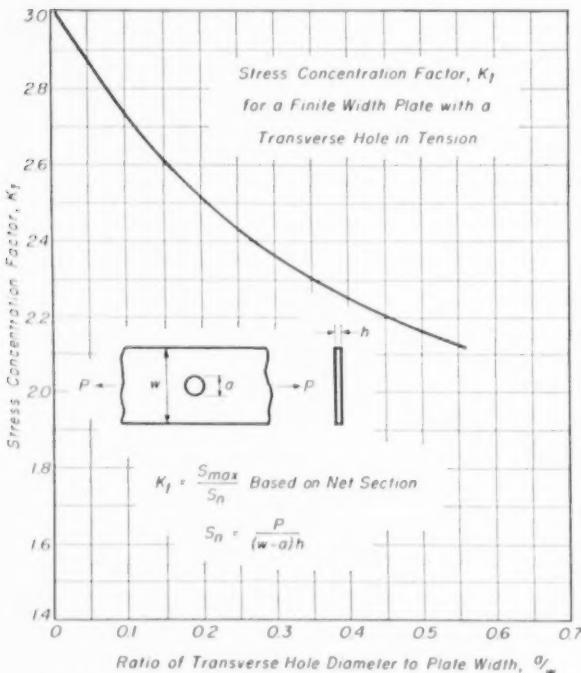


Fig. 5. Stress Concentration Factor for a Plate of Finite Width with a Transverse Hole (Tension)

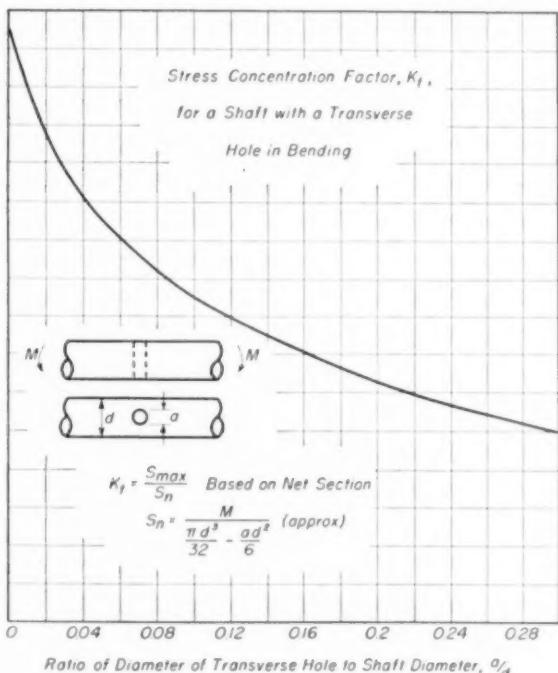


Fig. 6. Stress Concentration Factor for a Shaft with a Transverse Hole (Bending)

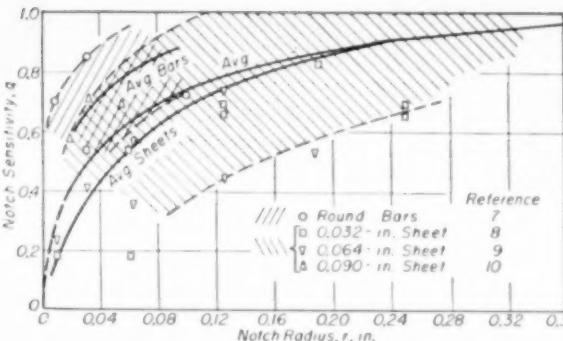


Fig. 7. Notch Sensitivity of Aluminum Alloy 24S-T4 Bar and 24S-T3 Sheet. Completely reversed axial loading

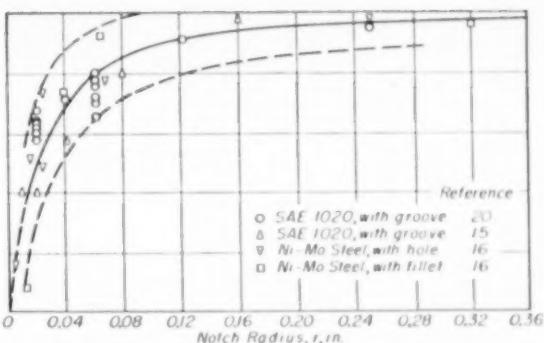


Fig. 8. Notch Sensitivity of Normalized 1020 and Nickel-Molybdenum Steels. Rotating beam specimens

as to cause a "tough" metal to fail in a brittle manner. Where brittle behavior is possible, it is well to be on the safe side by using K_t in stress calculations for static or vibratory loading. Exceptions to this rule are usually based on detailed knowledge and tests.

Ductile Metals. For metals that are ductile in the sense implied in the preceding paragraph, it is not customary to apply K_t for static loading.⁶ For vibratory or fatigue loading, the strength of a member is lowered by an amount which depends on notch acuity and the metal.

Notch Sensitivity

The degree to which a member is affected by stress concentration is known as "notch sensitivity", q , which is defined above in such a way that when $K_t = 1$, or no notch effect, $q = 0$; and when $K_t = K_t'$, or full theoretical notch effect, $q = 1$. This definition provides a scale of 0 to 1 with which to evaluate test data acquired from pieces of different size, shape and metal.

For a given metal, one would expect that K_t (or K_t') and the minimum notch contour radius, r (which in turn determines stress gradient), would be the principal variables affecting q . However, q depends much more on r than on K_t (or K_t') and some fairly reasonable curves^{7, 8} have been obtained for q versus r . When one considers the

differences in processing a given type of metal and in the machining and finishing of specimens, a considerable scatter of data is to be expected.

For various metals, one would expect that grain size would be an important factor in determining notch sensitivity. For example, in the presence of a stress gradient, the drop in stress across the highest stressed grain would be less for a fine-grained metal and would result in higher notch sensitivity.¹⁴ Tests have shown that for the proportions used in a variety of machine parts, the notch sensitivity is higher for fine-grained metal than for coarse-grained.^{9, 10}

Light Alloys. In Fig. 7 values of notch sensitivity, q , are plotted against notch radius, r , for 24S-T aluminum alloy for completely reversed axial load-

ing to 10 million cycles.⁷⁻¹¹ The data show a large amount of scatter, which may be caused partly by alignment difficulty in axial testing and partly by the necessity for providing auxiliary means of preventing buckling in completely reversed testing of sheet. Even though the scatter is large the q values for sheet specimens seem to be lower on the average than the q values for round bars, which would be expected from statistical considerations. It is recommended that the designer use $q = 1$ for bars or large sections even when they have fillets of small radii.

It has been suggested¹² that many of the high-strength wrought aluminum alloys, such as 14S-T, 61S-T and 75S-T, have fatigue notch factors similar to those for 24S-T.

Fewer data are available for magnesium alloys than for aluminum alloys. Fatigue notch sensitivities from flexure tests¹³ are within the scatter band shown in Fig. 7.

Annealed or Normalized Steels are found in railway axles, large rotors, pressure vessels, shafting and many other parts. In Fig. 8 is shown a plot of q versus r for typical data.^{15, 16, 20} The basic S_f value for unnotched specimens corresponds to conventional small specimens (0.3-in. diam for rotating beam). The size effect for unnotched specimens over a range from 0.3 to 2 in. is rather small.¹¹

Quenched and Tempered Steels are of prime importance for highly stressed

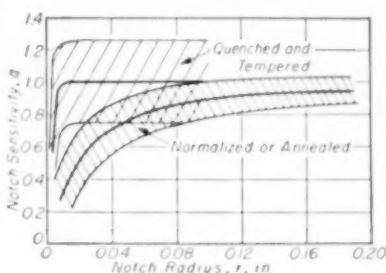


Fig. 9. Scatter Bands for Steels Under Alternating Bending

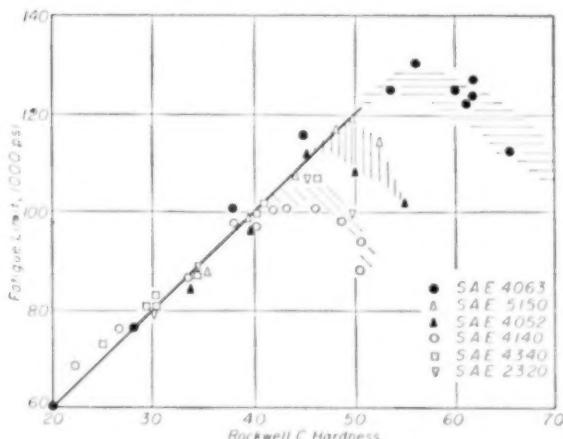


Fig. 10. Fatigue Limit of Oil Quenched and Tempered Alloy Steels. Unnotched rotating beam specimens

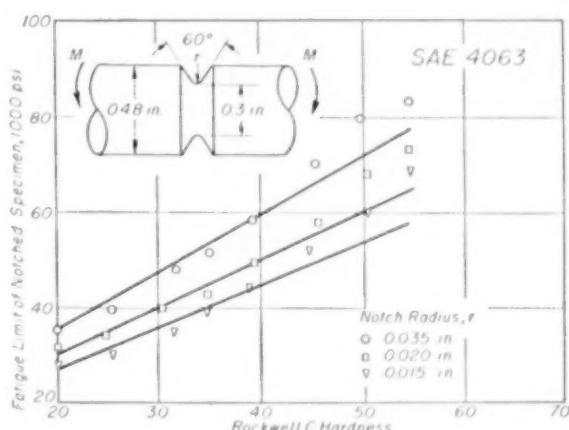


Fig. 11. Fatigue Limit of Notched Rotating Beam Specimens of Oil Quenched and Tempered 4063 Steel

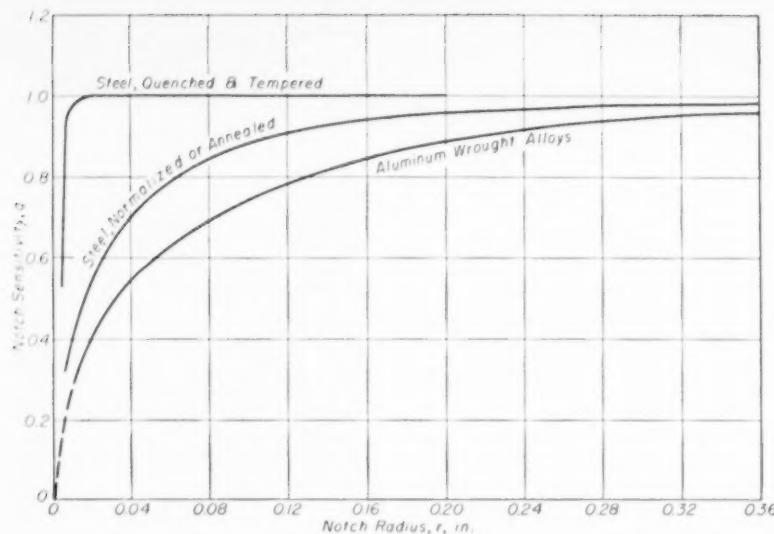


Fig. 12. Average Notch Sensitivity of Quenched and Tempered Steel, Normalized or Annealed Steel and Wrought Aluminum Alloys

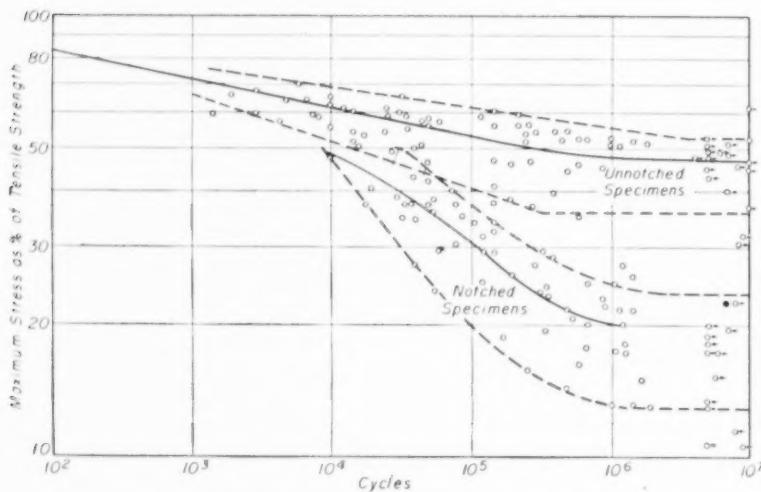


Fig. 13. Fatigue Data for Steels Under Completely Reversed Axial Loading

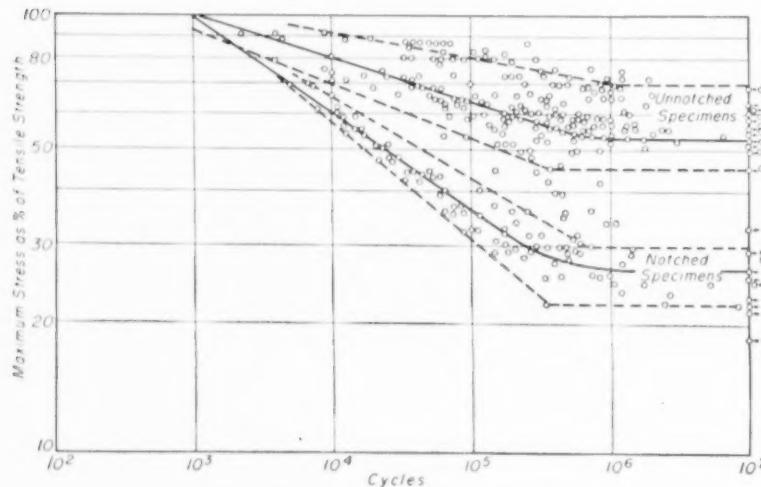


Fig. 14. Fatigue Data for Steels Under Rotating Beam Bending

machine parts. The data generally show greater scatter, so that experimental determinations become more difficult than for softer steels. A rough idea of relative scatter bands for steels is given in Fig. 9.

A survey of existing data on quenched and tempered steels indicates that, except for very small notch radii (of the order of 0.005 in. or less), a fatigue strength is obtained with notched specimens which corresponds on the average to dividing the fatigue limit for unnotched specimens by a theoretical factor, K_t , or K'_t . The scatter is so great that K_t and K'_t have been applied by various investigators; it seems that, although K_t is on the safe side and may be applicable for quite brittle steels, K'_t is in better general agreement with test results.

$$S_{Kf} = \frac{S_t}{K'_t}$$

This corresponds to $q = 1$, or full notch sensitivity. From a scientific viewpoint such a generalization would be too inclusive. From the designer's standpoint, however, it appears that taking $q = 1$ is reasonable in view of the information now available.

In Fig. 10 are shown fatigue limits for unnotched specimens of a group of six steels, oil quenched and tempered to various hardnesses.¹⁸ The straight line shown corresponds to the following rough rule which does not apply to metal at high hardness (shaded regions of Fig. 10):

$$S_t = 2000(R_c + 10)$$

where R_c = Rockwell C hardness

In Fig. 11 fatigue data¹⁹ are given for oil quenched and tempered SAE 4063 steel for notched specimens (three notch radii). The straight lines for the notched specimens correspond to the following relation with $K'_t = 1.68, 2.02$ and 2.26 for notch radii of $0.035, 0.020$ and 0.015 in., respectively:

$$S_{Kf} = \frac{2000(R_c + 10)}{K'_t}$$

It can be seen from Fig. 11 that the lines and plotted points (data) are in fair agreement for low and intermediate hardnesses, and the lines are on the safe side for high hardnesses. Note that the drooping characteristic at high hardness shown in Fig. 10 is much less pronounced in Fig. 11, probably because of stress-volume considerations. This means that while the relation for S_t for unnotched specimens is rather limited, the relation just given for S_{Kf} for notched specimens can apparently be used in design to cover the entire useful hardness range. Critical members nearly always involve stress concentration and, as shown by Fig. 11, full notch sensitivity ($q = 1$) is obtained for quenched and tempered steel. The data of Fig. 10 and 11 are in general agreement with data from other sources.¹⁹⁻²³

Various Metals. A summary of the average curves for the three foregoing types of material is given in Fig. 12. Some values for other ductile metals have been published: copper, brass and bronze,^{24, 25} nodular cast iron,²⁶ stainless steel,²¹ gas turbine alloys^{26, 27, 28} and titanium.²¹

Effect of Diameter. The results cited above for quenched and tempered steels apply to one diameter, 0.3 in. For large

diameters the fatigue limits are usually lower for both unnotched and notched members; the decrease is probably caused by residual stresses.*

Combined Steady and Alternating Stress Components

Any stress variation from S_{min} to S_{max} may be considered to consist of two components—a steady component S_s and an alternating component, S_a .

$$S_s = \frac{S_{min} + S_{max}}{2}$$

$$S_a = \frac{S_{max} - S_{min}}{2}$$

For a ductile metal, designers customarily apply K_t to the alternating component only.²¹ For brittle metals, or any condition leading to brittle behavior, K_t should be applied to both steady and alternating components, to be on the safe side.

Notch Effect for a Limited Number of Cycles

As can be seen from Fig. 13 and 14 the effect of a notch decreases from the limiting condition as the number of cycles, N , decreases.²² Some simple design rules have been proposed²³ on the basis of a linear reduction with log N . For aluminum alloys it has been suggested²⁴ that K_t be used up to a value of ($\frac{1}{4}$ yield strength/ K_t) and that a linear reduction be used above this value for the smaller number of cycles; from available data this recommendation appears reasonable.

Reducing Effects of Stress Concentration

Detail design can often be improved by altering the dimensions of a member in such a way as to achieve a less abrupt flow of stress at a critical section. For examples^{25, 26, 27} see Fig. 15.

Certain mechanical processing methods used to strengthen the surface of a member (shot peening, surface rolling and other surface working methods) are discussed in the next article. Case hardening,²⁸ nitriding²⁹ and other heat treatments can also be considered in the general category of surface strengthening methods. Strengthening is due partly to structural change and partly to favorable residual compressive stresses. From the standpoint of design, surface strengthening methods are of limited effectiveness in the absence of stress concentration (or decarburization). Consequently, conventional fatigue tests of unnotched specimens

*Since application of data from specimens of 0.3 in. diam to larger diameters would be on the "unsafe side", an extension is attempted, for design estimation purposes only, of the relation for S_{RF} based on a 10% drop¹⁴ of unnotched fatigue limit per inch of diameter (from 0.3 in. diam) for $R_c = 30$, a 20% drop at $R_c = 50$, and for other hardnesses in linear proportion:

$$S_{RF} =$$

$$2000 [R_c + 10] [1 + (0.1 R_c - 1) (0.3 - d)] / 20$$

for diameter, d , $\frac{1}{4}$ to $1\frac{1}{2}$ in.

This relation is based on limited data. When additional information for specimens of large diameter becomes available, the appropriate constants in the above relation can be easily modified.

mens do not reveal the full potentialities of these methods for strengthening actual parts.^{14, 20} For the relatively steep gradients usually found at regions of stress concentration in machine parts, the foregoing methods of surface working, if properly carried out, are very effective in increasing fatigue strength. Examples are given in the next article in this Supplement.

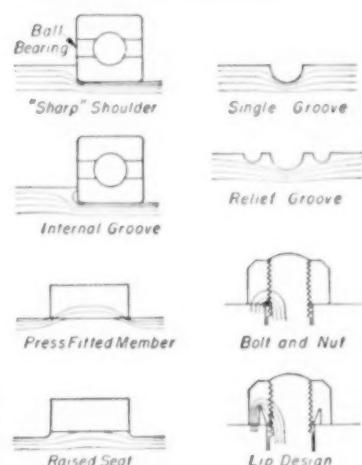


Fig. 15. Examples of Improved Design for Better Stress Distribution. Flow lines schematic

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Shot Peening and Other Surface Working Processes

By the ASM Committee on Shot Peening

THIS ARTICLE describes shot peening and three other working processes for improving the fatigue resistance of manufactured parts. It is intended as an aid in selecting the most suitable process and in applying the processes in production.

The origin of surface working goes back to early metalsmiths who improved the strength of their hand forged products by cold hammer peening after forging. Not until 1929, however, was it recognized that surface cold working by rolling increases fatigue resistance. In the same year, shot peening was first applied in a controlled production process by F. P. Zimmerli.

Despite the emergence of surface cold working from a blacksmith's art of unknown merit to a production process of proven value for increasing fatigue resistance, it was confined mainly to the spring industry until the outbreak of the second World War. The method was widely publicized during the war as a means for obtaining high fatigue strength in steel aircraft engine parts without the standard time-consuming and tedious practice of polishing all surfaces. During and since the war, surface working has become widely accepted as a production process for increasing fatigue resistance. To date it has been used primarily to improve the fatigue strength of existing designs; in springs, however, its effect has been incorporated in new design calculations. Its use as a factor in redesign of other components appears to have good possibilities.

Advantages of surface working to increase fatigue resistance of an existing design are that (1) no design changes or modifications of other processing are required; (2) the improvement is generally of a higher order than can be expected from improvements in surface finish or minor modifications in metal or heat treatment; and (3) the improvement in fatigue resistance is additive to other factors, notably reduced stress concentration and stronger metal.

In new designs, surface working may save weight by raising allowable unit stresses, save money by using cheaper metals and heat treatments, and give the designer more latitude in achieving a simpler design. The process will not counteract the harmful effect of surface defects such as seams, laps and quenching cracks.

Three basic changes generally occur in working the metal surface, and it is likely that all three are in part responsible for improved fatigue resistance.

Supplements the Mechanical Processing section of the article on Service Failures, pages 249 to 252 of the 1948 ASM Metals Handbook

Hand or Mechanical Peening can be applied rapidly to small areas without affecting the rest of the piece, the only limitation being accessibility. Equipment is almost negligible in cost. However, control must be left largely to the operator. Usually, this type of peening is applicable only to small surface areas and hole walls.

Prestressing involves stressing a part beyond its yield strength, either statically or dynamically, in the same manner that it will be stressed in service, thereby cold working the metal and leaving favorable residual compressive stresses at the critically stressed areas of the structure. In complex parts where surface finish must be maintained on critically stressed broad surfaces, or where the area is otherwise inaccessible, it may be the only applicable method.

Disadvantages are: The part may be excessively distorted; control may be difficult; and the method is applicable only to ductile metals. Improvement in fatigue properties is usually less than for the peening or rolling methods.

Extent of Improvement

Gains in fatigue resistance are proportional to the amount of surface working, up to a certain maximum. Although the surface can be "over-worked", losing part or all of the benefits, the maximum improvement is obtained over a fairly broad range of cold work and overworking is rather easily avoided.

In the absence of gross surface defects, surface working produces a fairly consistent high fatigue level, regardless of the original surface finish. Therefore, prior polishing or otherwise improving the finish is often unnecessary.

Even slight decarburization appears to reduce the fatigue resistance of steel parts to a value consistent with the strength of the decarburized skin, regardless of the properties of the base steel. Surface working helps to correct this, especially for shallow decarburization.

Residual Surface Stresses

Grinding and welding may develop residual tensile stresses; straightening induces both tensile and compressive stresses; heat treating may produce either compression or tension. Thus, fatigue resistance to tensile cycles (as are usual) is affected favorably or adversely depending on whether the residual stresses are compressive or tensile. Surface working produces a compressive surface stress, regardless of the initial stress pattern. Hence, if the existing stress is tensile, appreciable improvement may be expected; if the existing stress is compressive, the improvement will be much less.

Surface working is more effective on recessed stress raisers such as oil holes and fillets than on projecting stress raisers such as sharp projecting corners. In fact, a decrease in fatigue resistance is possible after surface working sharp projections, indicating that they should be rounded off.

Elevated temperatures produce stress relieving and tempering effects which may lower or entirely remove the benefits of surface working. Deleterious temperatures may be below 250°F for some nonferrous metals, and 500°F for

Subdivisions	Page
Surface Working Processes	104
Extent of Improvement	104
Residual Surface Stresses	104
Shot Peening	105
Surface Rolling	106
Hand and Mechanical	
Peening	107
Prestressing	108

In the first place the surface becomes stressed in compression, and can sustain higher cyclic stresses in tension without failure than neutral surfaces or those having residual tensile stresses. Secondly, the surface is strengthened by cold working. Finally, in some cold working processes, machining or grinding lines are obliterated, leaving a surface finish of improved stress-distributing characteristics.

Surface Working Processes

Selection of a surface working process is based on the advantages and disadvantages which follow.

Shot Peening is a process in which shot of controlled size, shape and properties is propelled at high velocity against the surface to be treated, for a specific time. It can be established and controlled better than the other methods. Differing parts can be handled with only minor changes in fixtures. Large areas (and *all* surfaces of some types of parts, such as springs) can be treated, usually at a high production rate. Sometimes shot peening eliminates separate descaling and deburring operations.

The process has two disadvantages: Areas where shot peening is not desired must be masked during the process, and the shot will produce a high rate of wear on metal fixtures and masks.

Rolling of selected surfaces, such as the fillets of shafts, by suitable devices, exerts heavy unit pressure exceeding the compressive yield strength of the metal.

Advantages are: The working action can be confined to a specific area of the part. Equipment may be simple: large shafts having only one area that requires the treatment, can be worked on the same lathe or other turning equipment used in shaping the part, with little investment in auxiliary equipment. For complex parts such as crankshafts, where masking of crankpins and journals might be prohibitive for shot peening, equipment can be devised to roll all fillets simultaneously at a high rate.

Disadvantages are: Establishing the procedure and controlling it are not so simple and exact as for shot peening. Furthermore, the process can be applied only to surfaces of parts whose size and shape are adaptable to rolling.

most ferrous metals; the higher the temperature, the greater the loss.

The surface layer accounting for increased fatigue resistance from surface working is quite shallow, and operations which remove part of this layer can appreciably reduce the benefits. The safest rule is to remove no metal after surface working. Subsequent straightening should also be avoided.

Shot Peening

The principal components of shot peening equipment are a shot propelling device, shot cycling equipment (including devices for the removal of spent shot and addition of new), and a work handling conveyor. All portions exposed to the shot stream are enclosed to confine the shot and permit it to be recycled.

Propelling and controlling the shot stream are of major importance. Commercial machines are either air blast or centrifugal blast. The former introduce the shot, either by gravity or direct pressure, into a stream of air directed through a nozzle onto the work to be peened.

In centrifugal blast machines, the shot is fed into a spinning wheel with radial blades, and is thrown from these blades by centrifugal force, in a fan shaped stream, onto the surface to be peened.

Regardless of the type of shot propulsion, all machines incorporate a mechanism for cycling the shot and for separating undersize or broken shot and replacing it with new.

With few exceptions, some relative motion in addition to straight-line travel is necessary between the work and the shot stream for uniform peening of anything but a flat surface. This is usually achieved by rotating the work in an appropriate manner. A simple flange or hub, for example, may be efficiently peened on a single rotary table revolved about a vertical axis directly under the shot stream. A more complicated part such as a ring gear may be placed on the outer edge of a rotating table while the gear itself is rotated relative to the table. The shot stream must always be directed so as to produce the desired coverage in critical areas of the part.

Axle shafts, suspension coil springs, sway bars and crankshafts are most commonly moved through the shot stream on a series of rolls which rotate the parts about their own axis while they are passed under the shot. Many small parts, peened in large quantities, may be tumbled under a shot stream in a batch operation. Flat pieces, such as spring leaves, are passed through the shot stream on belt conveyors.

Some portion of the part may have

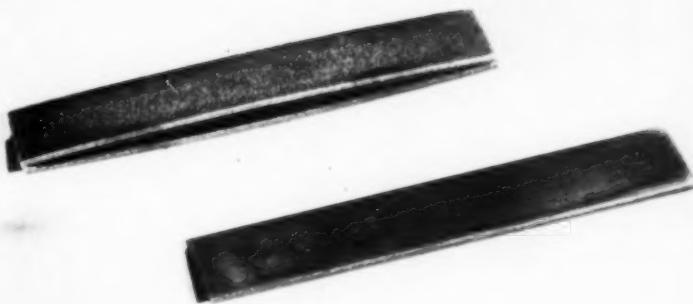


Fig. 1. Almen "A" Test Strips Before and After Shot Peening (Full Size)

to be masked, to prevent exposure to the shot, by fabric or rubber tape, steel or rubber fixtures, or a combination.

Quality Control of shot peening at the site of the operation can be established only through the properties of the shot stream itself, including shot characteristics, velocity and density, and through the duration and angle of impingement.

Initially, these two factors are generally established by trial and error. New parts are experimentally shot peened and then fatigue tested until the optimum or desired fatigue properties are established.

Properties of the shot stream are evaluated and controlled through measurement of shot quality and blast intensity. Shot is generally of iron or steel, although some nonferrous and nonmetallic materials are used. Shot is classified according to size, generally varying from 1/64 to 3/32 in. diam. Cast iron shot is available as balls Rockwell C 20 to 60 or harder. Steel shot is available as balls or short cylinders and may be cast, forged or cut from wire, all supplied in a wide range of hardness. Once the type and size have been established, quality of the new shot is maintained through sampling inspection for size, shape and hardness.

Blast intensity is generally measured at the point of exposure of an actual part. Thus, it is not an inherent quality of the shot stream but depends on the conditions of exposure. This property is referred to as "arc height" and is measured through the use of small flat test strips of steel, known as Almen strips, which are clamped to a solid steel block while one side is exposed to the shot. After exposure, the test strips will have a convex curvature

on the peened side, as shown in Fig. 1. The greater the blast intensity at the exposed area, the greater the curvature or arc height of the Almen test strip.

Two thicknesses of strip are used: the "A" strip, approximately 3 by $\frac{3}{4}$ by 0.050 in., is used for light work, while the "C" strip, the same except 0.0938 in. thick, is for heavier work. Both are Rockwell C 44 to 50. The steel block to which the test strips are clamped is 3 by $1\frac{1}{2}$ by $\frac{3}{8}$ in., Rockwell C 62 to 65. Arc height measurements are made on an Almen gage, which registers a combination of arc both longitudinally and transversely on the strip and reads in thousandths of an inch.

Intensity measurements vary considerably depending on time and location of the test strips in relation to the shot stream, so it is essential that their exposure be as nearly identical as possible with that of the critical surfaces of the parts in process. The blocks and test strips can be fastened to an actual part or to a dummy of similar proportions, at one or more of the critical surfaces.

Finally, "coverage", or the proportion of a surface which has had actual physical contact with one or more shot particles, must be measured and regulated. Sometimes coverage can be directly evaluated on shot peened parts, but usually a visual examination of the exposed surface, or a replica thereof, is necessary, followed by estimation—either directly or through comparison with previously prepared standards—of the percentage of the area which has had direct contact with shot particles.

It is generally much easier to measure coverage on an Almen strip than on the actual part. The estimation or calculation of coverage from a test strip examined at low magnification is further simplified if the strip has been polished lightly in one direction prior to exposure to the shot stream.

Examples. Representative data for taxicab steering knuckles are listed in Table I; all the parts were similarly quenched and tempered; the peened knuckles were blasted with 0.028-in. cut wire shot in an airless cabinet. All fatigue tests were in reversed bending on a resonant tuning-fork type of machine with the steering knuckles used as the flexible member of the fork. The data are typical of improvement by peening a machined surface of a low-alloy steel at a readily machinable

Table I. Fatigue Tests of Taxicab Steering Knuckles

Steel	Condition	Brinell Hardness Number	Nominal Fatigue Limit, psi	Improvement, %
4052	Standard	255 to 285	33,000	-
4052	Standard	285 to 321	39,200	19
4052	Shot Peened	255 to 285	42,200	28
5150	Standard	255 to 285	35,600	8
1340	Standard	255 to 285	34,000	3

Bearing diam., $1\frac{1}{16}$ in.; fillet radius, $\frac{1}{8}$ in.

M. F. Garwood, H. H. Zurburg, M. A. Erickson, Correlation of Laboratory Tests and Service Performance, "Interpretation of Tests and Correlation with Service", ASM, 1951

hardness, in comparison with increasing the hardness to the maximum level practical for machinability.

Results for quenched and tempered axle shafts of 4063 steel at 388 to 444 Brinell are as follows:

Shot Size, in.	Wheel Speed, rpm	Intensity, A2 ^(a)
0.018 to 0.024	2250	0.012
0.024 to 0.031	2000	0.017
0.031 to 0.040	1800	0.024

Travel through blast was at the rate of 21 ft per min (7 shafts per min).

(a) 0.012 A2 means an arc height of 0.012 in. as measured on an A-strip by the Almen No. 2 gage.

Three groups of shafts were shot peened under the cited conditions and fatigue tested in rotating bending. Improvement in each group was nearly identical, the fatigue limit increasing from 26,000 to 44,000 psi, or 75%. For verification, shot peened shafts were installed in heavy-duty service in which isolated failures had previously occurred in the unpeened axle shafts. Over 100,000 miles of operation were clocked in each of 50 test vehicles without failure.

Figure 2 shows operating stresses and temperatures permissible in carbon steel valve springs in both the shot peened and untreated condition. Springs were fatigue tested for 10 million compressions in a heated chamber.

Tests on a variety of spring metals from -75 to 650°F show both the marked increase in operating stresses and the persistence of favorable effects to about 250°F.

Numerous examples of specific methods of shot peening on both coil and leaf springs may be found in Section IX

of the SAE Manual on Shot Peening.

Tests on truck ring gears and pinions with a carburized surface of Rockwell C 58 to 62 show an average life of 381,400 pinion cycles for 13 units shot peened, compared with 119,700 for 13 units not shot peened. Parts were shot peened on a rotary table machine to an arc height of 0.017 in. on the ring gear and 0.015 in. on the pinion. Fatigue tests were run in a Gleason axle-testing machine with 78,520 in.-lb torque load and 33 rpm on the axle shafts. These data clearly indicate that shot peening has a beneficial effect on fatigue life even at Rockwell C 60 or higher.

The successful application of shot peening to a variety of metals over a wide range of strength is summarized in Table II.

Conventional shot peening of magnesium samples reduced fatigue strengths as much as 60%; small shot at high velocity overworked the surface. When

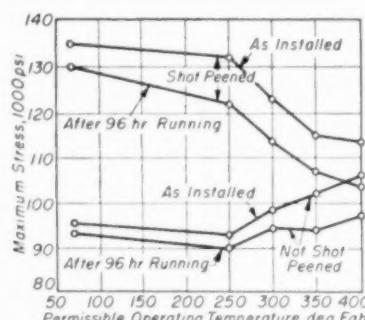


Fig. 2. Operating Stresses and Temperatures Permissible in Carbon Steel Valve Springs for an Infinite Number of Load Applications

the magnesium samples were peened with 3/16-in. diam shot falling from a height of 24 to 48 ft, the fatigue limit improved as follows:

As cast	8,000 psi
Machined and polished	10,000
Peened, 3/16-in. diam shot	12,000

Rubbing or burnishing produced the same beneficial surface effect. A spherically tipped tool, mounted in a fixed or spring-loaded position in a toolstock was traversed at 0.006 in. per stroke across the surface in a shaper or lathe. The tool pressed into the work 0.004 to 0.015 in. beyond touch contact. This rubbing method is especially suitable for machined magnesium surfaces, while the peening technique can be used on unfinished or as-cast surfaces.

Forming by Peening. Shot peening has been used to form as well as strengthen integrally stiffened aircraft wing panels machined from slabs of 75S-T6 aluminum alloy, which must be curved for aerodynamic reasons. The large size of the panels (32 ft by 46 in.) prevented hot forming; cold forming produced surface tensile stresses of 20,000 psi or more, which were alleviated by shot peening the panels on the tension side. Proper curvature of the panels could be obtained by shot peening alone, with careful control of intensity. The need for conventional cold forming methods thereby was avoided and the high compressive stresses induced by peening virtually eliminated the possibility of fatigue failures.

Surface Rolling

Some applications of surface rolling are noted on page 251 of the 1948 Handbook, in the section on causes of service failures. Probably the principal

Table II. Effect of Shot Peening on Fatigue Strength

Metal	Stress Cycle	Surface Condition as Received	Fatigue Limit for 10,000,000 Cycles of Stress, psi			Gain by Shot Peening, %	
			As Received	Polished	Shot Peened ^(a)	Over "As Received"	Over Polished
Nonferrous Metals							
Duralumin	Reversed bending	Fine turned	17,100	.....	19,900	16	..
Magnesium alloy							
Wrought (AZ 31) ^(b)	Reversed bending	Fine turned	13,500	.....	17,100	26	..
Cast ^(b)	Reversed bending	Fine turned	7,100	.....	8,800	24	..
Phosphor bronze wire	Torsion, 20,000 psi to max	As drawn	35,000	.....	50,000	43	..
Phosphor bronze sheet	Reversed bending	As rolled	31,600	.....	47,900	52	..
Steels, Including Stainless Steels							
SAE 1020	Reversed bending	As rolled	28,000	34,500	37,500	34	0
SAE 1045, induction hardened	Reversed bending	As hardened	50,000	.....	75,000	50	..
SAE 1045, normalized and tempered	Reversed bending	As rolled	.....	31,000	34,000	..	10
SAE 1050 plate	Reversed bending	As rolled	.....	37,000	47,000	..	27
Rail steel	Max compression to 20% tension	As rolled	59,000	.....	78,000	32	..
0.85% C spring wire	Torsion, 20,000 psi to max	As drawn	95,000	.....	135,000	42	..
SAE 1095 music wire	Torsion, 20,000 psi to max	As drawn	90,000	.....	135,000	50	..
SAE X4340 oil quenched and tempered	Reversed bending	As rolled	.....	66,500	78,000	..	16
Ni-Cr-Mo, carburized and heat treated	Reversed bending	As heat treated	58,000	68,500	71,500	23	4
9470, carburized	Reversed bending	As carburized	100,000	.....	150,000	50	..
9420, carburized	Reversed bending	As carburized	100,000	.....	153,000	53	..
18-8 stainless wire	Torsion, 20,000 psi to max	As drawn	65,000	.....	110,000	69	..
18-8 stainless bar	Torsion, zero to max	As rolled	46,000	.....	92,000	100	..
13-3 stainless wire	Torsion, 20,000 psi to max	As drawn	80,000	.....	120,000	50	..

(a) Not polished before shot peening. (b) See text for description of special technique applicable to magnesium.

From "Shot Peening", American Wheelabrator & Equipment Corp., 4th edition, 1951

application of this method is on the fillets of shafts subjected to torsion and bending. In surface rolling, a suitably shaped roller is pressed into the fillet while the shaft is rotating under a specific load for a predetermined number of revolutions, sufficient to iron out and smooth the surface by plastic flow. The process ordinarily is applied to straight shafts on a lathe, with the roller mounted in a specially designed spring-loaded mechanism held in a standard single-point tool holder and fed into the fillet by the tool feed mechanism of the lathe. Figure 3 illustrates a typical rolling tool of this type.

With crankshafts, where multiple fillets are involved and the rotation of the crankpin fillets is not concentric with the central axis of the shaft, multiple rollers can be mounted in hydraulically operated clamp fixtures attached to guided follower-arms.

The roller mounting and method of generating and maintaining the required force vary considerably with different users. The roller is usually pressed lightly onto a pin which rotates in bushings mounted in the holder. Sufficient side clearance is given to the roller so that it can slide laterally and center itself in the fillet.

Two types of rollers are in commercial use. The first, a plain type as illustrated in Fig. 4, is used effectively for fillets having a radius of 1/32 in. or less. The rolling periphery has a radius at the low limit of the fillet radius tolerance, which generates, by plastic flow, a new shaft radius conforming to the roller periphery. An applied force of less than 100 lb is usually sufficient for this small radius, and greatly simplifies both the roller and shaft mounting. Very few shaft revolutions are required to obtain the maximum effect; in one application ten revolutions of the shaft are sufficient.

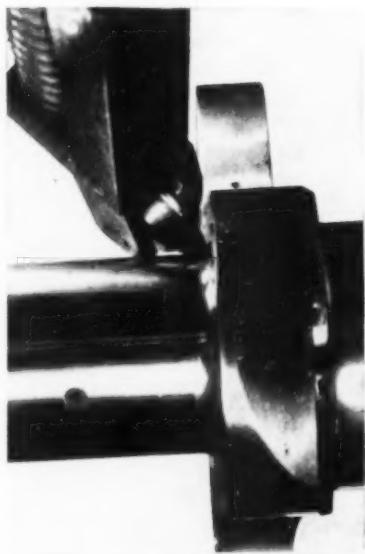


Fig. 3. Typical Plain Roller Tool Mounted in a Lathe and Spring Loaded to Apply Force to the Crankshaft Fillet Over Which It Travels (Research Laboratories Div., General Motors Corp.)

Rollers of oil-hardening tool steel at Rockwell C 62 to 65 have given excellent results, with dimensions as noted below Fig. 4. The plain roller normally serves for several thousand pieces and its cost is almost negligible.

It would be most desirable if all fillet rolling could be done with a plain roller merely by making the radius of the roller periphery larger as the radius of the shaft fillet increases. However, the required force on the roller rapidly reaches high values where the roller and shaft mountings, as well as the means of generating the required force, become quite complex. (The normal manufacturing variation in fillet radius is an important part of this same problem.) The Jackman wedge roller (Fig. 5) offers a solution; it can roll large fillets with a small applied force and at the same time is unaffected by the normal manufacturing variations in fillet radius. The wide portion of the wedge rolls the extremities of the fillet while the point of the wedge

of fillets, primarily because of differences in straightening. Rolling these fillets improves the fatigue limit by 55% on straightened shafts and 24% on unstraightened shafts; both straight-

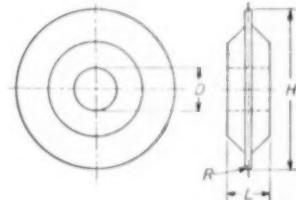


Fig. 4. Sketch of Plain Circular Roller Tool. Radius (R) at the periphery is the low limit of the fillet radius tolerance. The major diameter (H) is about 2 in.; width (L) and hole diameter (D) are about 1/2 in.

ened and unstraightened crankshafts show the same fatigue characteristics after rolling.

Cold rolling with steel balls is another means for strengthening fillets. This has increased the limiting stress on gray iron crankshafts by 60% for reversed bending and by 80% for "one-way" loading. The method was to use three steel balls equally spaced around the fillet and held in place by a loading ring. The ring was assembled on the crankpin and loads applied through four coil springs, compressed by a screw attachment so as to produce a deformation of about 0.003 in. in the fillets. The small ridge of metal formed at the junction of fillet and journal was removed by a simple polishing operation.

Hand and Mechanical Peening

Hand peening is especially suited to isolated stress raisers such as the exposed edges of holes which can be cold worked with one or a few hammer blows. The process is extremely simple and despite its apparent lack of precision it improves fatigue resistance markedly where applicable. About the only requirement is that a smooth surface without nicks or notches be produced. The edges of a hole can be peened by striking a cone-shaped tool while the cone is centered over the hole, thereby chamfering the hole by cold work.

Each hand application suggests its own peening tool. Control rests entirely with the operator and complete instructions on the job are mandatory.

In mechanical peening, the tool is hydraulically or electrically driven and usually delivers a specified number of blows of lesser intensity.

Mechanical peening has been successfully done by a small air-driven "pencil grinder", reworked to give a peening tool by unbalancing the shaft as indicated in Fig. 6. In operation the peening hammer, fixed to the end of the shaft, vibrates rapidly. This tool can be purchased as shown, without the hammer. It is especially useful for peening the walls of holes, but can also be used on several other types of surfaces.

Table II on page 250 of the 1948 Handbook quotes an increase in fatigue limit up to 33% from peening or pre-

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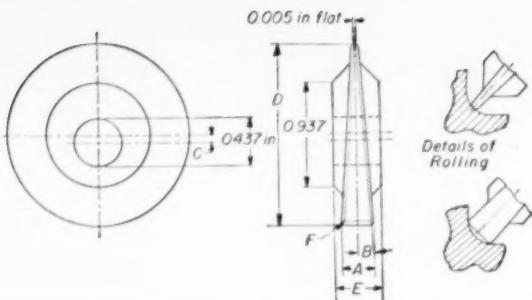
works the center, as shown in the two detail sketches at the right-hand side of Fig. 5. The other points on the wedge contact the intermediate points in the fillet. As the shaft rotates, the roller edge rides up and down on each side of the fillet in a sort of kneading action.

The dimensions shown in Fig. 5 are recommended for rolling shaft radii of different sizes. More cycles are required to roll a fillet with the wedge roller than with a plain roller; 200 to 600 rotations at 60 to 200 lb pressure is typical. Life is less than for plain rollers because of the longer rolling time but tool cost per fillet is still small.

A lubricant is used in all rolling operations, and is especially necessary with the wedge roller.

At present there is only one satisfactory method of inspecting the rolling operation for quality in production — visual examination of the finished pieces for smoothness and the obvious imprint of the roller in the fillet. Failure of the rolling edges, improper rotation of the roller, and failure of the roller to center properly in the fillet are the principal difficulties encountered; however, with proper tooling, little trouble is experienced.

Numerous examples of increased fatigue resistance from surface rolling have been reported. Large increases have been achieved with fillets of both forged and cast crankshafts. Diesel engine crankshafts show a wide variation in fatigue resistance before rolling



For Fillet Radius, in.	A, in.	B	C, in.	D, in.	E, in.	F, in.
$\frac{1}{16}$ to $\frac{1}{8}$	0.174	1° 57'	0.030	1.625	0.437	0.031
$\frac{1}{8}$ to $\frac{1}{4}$	0.284	3° 58'	0.060	1.625	0.437	0.031
$\frac{1}{4}$ to $\frac{1}{2}$	0.435	6° 04'	0.080	1.562	0.460	0.0625
$\frac{1}{2}$ to $\frac{3}{8}$	0.612	6° 52'	0.090	2.125	0.687	0.0625

Fig. 5. Sketch of Wedge-Shaped Roller (C. W. Jackman, U. S. Patent 2,357,515). Dimensional details for different fillet radii are from Research Laboratories Div., General Motors Corp.

stressing holes with a conical stamp, and a 44% gain with a conical pin.

Fatigue limit (reversed torsion) of crankshaft sections has been increased about 20% by peening the oil holes in the shafts with a pneumatic hammer peening tool, using different heads for the chamfered surfaces at the oil hole exits and the surfaces below the chamfer.

Similar peening of malleable iron, followed by testing in bending fatigue with unidirectional cantilever loading, showed all unpeened specimens failing at less than 250,000 cycles while four hammer peened specimens ran 5,000,000 cycles without failure.

Prestressing

In prestressing, a part is loaded in the same manner anticipated in operation. The critically stressed points of the structure are permanently deformed in tension during the load application and when the applied load is released the stress reverses, leaving these deformed points under residual compression and thus increasing fatigue resistance. Measurements from preselected gage points determine whether the required set has taken place. The pre-

setting, "scrapping" or "bulldozing" of springs; the prespinning of impellers; and the preloading of gun barrels (autofrettage) are well known examples of the process. It is applicable only to ductile materials.

In one example, residual compressive stresses were applied at the root of an annular notch, by tensile preloading of initially stress-free notched specimens to a nominal stress of 25 tons per sq in. The specimen was an extruded section of aluminum alloy and the width at the top of the notch increased 3 to 4% after prestressing. Fatigue resistance

in rotating cantilever tests was increased 100%.

Tests on laminated springs subjected to "scrapping" showed an increase of about 30% in fatigue resistance over those not prestressed. Tests were on low-chromium steel plates prestressed by four-point loading until a permanent deflection of about 0.05 in. was obtained on a span of 4 in. In the subsequent plane-bending fatigue tests, the direction of loading was the same as in scrapping.

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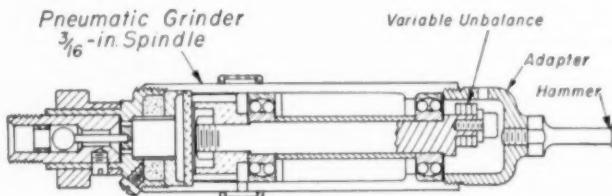


Fig. 6. Standard Pneumatic Portable Grinder Converted to a Peening Tool by Incorporating a Centrifugal Unbalance on the Shaft (Research Laboratories Div., General Motors Corp.)

Selected Definitions of Fatigue Terms^(a)

Fatigue Strength, S_u . The greatest stress which can be sustained for a given number of stress cycles without fracture. The number of cycles should always be given. The same considerations as for fatigue limit apply where the mean stress is not zero.

Fatigue Limit (or Endurance Limit^(b)), S_e . The limiting value of the stress below which a material can presumably endure an infinite number of stress cycles, that is, the stress at which the $S-N$ diagram becomes horizontal and appears to remain so. It should be noted that certain materials and environments preclude the attainment of a fatigue limit.

If the stress is not completely reversed, it is necessary to state what is meant by the fatigue limit. It may be expressed in terms of the alternating stress amplitude or the maxi-

mum stress; whichever method is used, it is also necessary to state the value of the mean stress, minimum stress, or stress ratio.

Fatigue Life, N . The number of stress cycles which can be sustained for a given test condition.

Fatigue Ratio (or Endurance Ratio). The ratio of the fatigue limit (or endurance limit), S_e , or fatigue strength, S_u , to the static tensile strength, S_s , that is, S_e/S_s or S_u/S_s .

Fatigue Strength Reduction Factor, K_f . The ratio of the fatigue strength of a member or specimen with no stress concentration to the fatigue strength with stress concentration. K_f has no meaning unless the geometry, size, and material of the member or specimen and stress range are stated.

S-N Diagram. A plot of stress

against number of cycles to failure. It is usually plotted S versus $\log N$, but a plot of $\log S$ versus $\log N$ is sometimes used.

Stress Ratio, R . The algebraic ratio of the minimum stress and the maximum stress in one cycle, that is, $R = S_{min}/S_{max}$.

Stress Concentration Factor, K_c . The ratio of the greatest stress in the region of a notch or other stress concentrator as determined by advanced theory, photoelasticity, or direct measurement of elastic strain, to the corresponding nominal stress.

Mean Stress (or Steady Stress Component), S_m . The algebraic mean of the maximum and minimum stress in 1 cycle, that is, $S_m = (S_{max} + S_{min})/2$.

(a) These definitions are from the "Manual on Fatigue Testing", ASTM, 1949. (b) "Fatigue limit" is preferred.

Design of Ferrous Castings

By the ASM Committee on Cast Metals

COST AND PERFORMANCE are the basic factors influencing good casting design. The engineer should choose the structure and metal that will produce the desired service results at the lowest over-all cost, not in terms of cost per pound of cast metal, but as minimum total unit cost for the finished product.

The economic status of ferrous castings is reflected in Bureau of Census figures on total shipments for 1953. They show 13,630,715 net tons of gray iron, 967,065 tons of malleable iron, and 1,829,287 tons of steel castings. Gray iron, of course, is the lowest in cost, malleable next and steel the highest of the three. Nodular (or ductile) iron castings, introduced in 1948, are higher in cost than malleable iron castings.

Consultation on preliminary casting designs by the foundryman and the design engineer is always advisable, since the former frequently can suggest modifications to simplify molding, eliminate expensive cores or chills and decrease the probability of high residual stresses in the casting. The designer also needs familiarity with foundry technology and the limitations of metal castability.

General Design Principles

Sections of castings no thicker than required for strength should be proportioned and disposed so that those most distant from the point where the casting is to be fed will solidify first, with solidification proceeding directionally toward heads or risers, where the metal is hottest. The foundryman's plea for section uniformity is based on his ability to obtain directional solidification in a casting of approximately uniform section, by the arrangement and location of gates and risers and through control of metal temperature and pouring speed.

Designers should place heavy sections where they can be fed adequately. By chills and other devices the foundry may be able to accelerate the normal, slow cooling of a poorly located heavy section, but such practices increase manufacturing cost.

Many casting production problems are traceable to inferior design. Frequent errors are variable metal thicknesses, absence of fillets, inadequate fillets, misplaced bosses and poor core design. A boss in a critical location or a reinforcing rib may increase cost considerably by requiring the use of cores, and may also result in unsoundness, high residual stress and distortion in the casting.

Whenever possible, section thickness throughout should be held as uniform as compatible with over-all design considerations. If thickness must be varied, it should be increased gradually.

Supplements the articles on Cast Iron, Malleable Iron and Steel Castings, on pages 505 to 526 of the 1948 ASM Metals Handbook

metal composition. Explanatory comment below each sketch gives further details of recommended practices.



Incorrect



Correct

Bosses or pads which increase metal thickness in thin walls, or in thick sections surrounding thin areas, should be blended gradually into the body of the casting by tapering or flattening filets, to avoid localized hot spots.



Poor



Not Recommended

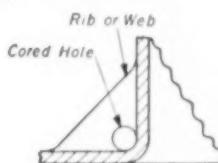


Good

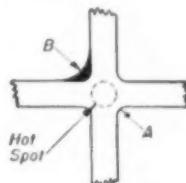


Sometimes Best

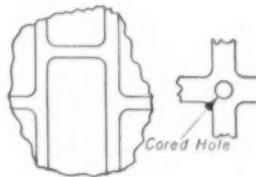
Best execution of fillets and taper calls for gradual changes in section, with generous radii and no sharp corners.



Concentration of metal should be minimized by cored openings in webs and ribs. These openings should be as large as possible, commensurate with strength and stiffness.

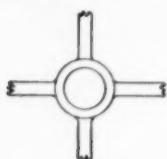


Where sections cross, the mass of metal is enlarged at the crossing point **A** and will retard cooling there. This condition is aggravated by excessively large fillets **B**.

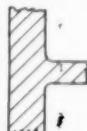


Staggering ribs or webs avoids concentration of cast metal; a cored hole where ribs must cross eliminates hot spots. However, the size of the core is

a limiting factor in applications that must have all cores thoroughly removed from the casting.



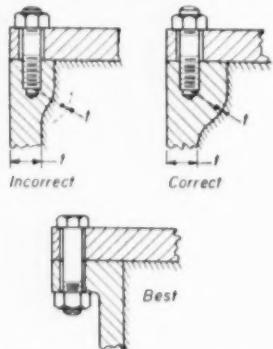
A web with ribs extending from its periphery is an excellent design on large flat plates. The section of the circular web may be less than the ribs.



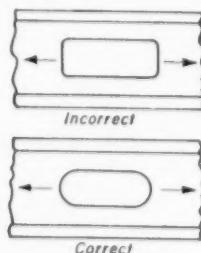
Thin ribs joined to a heavier section are inadvisable. They freeze first and pull away from the heavier mass. Ribs are of little value in tension and should be used in compression only.



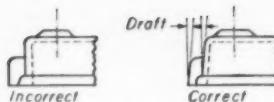
In unified L or V sections, radii should be provided at junctions t_1 to make the section at this point thinner than the principal width t_2 . Y-sections should have a triangular cored hole to reduce the thickness at the junction.



An inserted stud will not restore the strength of the original thickness. The wall adjacent to drilled holes should be equivalent to the main body of the casting. (Pressure on shaded side)



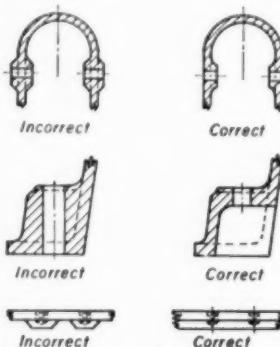
Oval-shaped cored holes in ribs or webs are preferred, with the longest dimension in the direction of the stress.



Patterns without draft make molding difficult and costly. Standard draft angle is 3 deg.



Undercuts should be dispensed with wherever possible.



Outside bosses (top) should be omitted to facilitate straight pattern draft. Redesign (center) often will save weight, metal and machining time. A continuous rib (bottom) instead of a series of bosses permits shifting the location of holes.

Testing and Inspection

Mechanical properties of test bars are included in various specifications for castings (see "Mechanical Tests of Castings", page 136, 1948 Metals Handbook). They inform the foundry whether processes are in control and indicate to the designer whether he has obtained the metal specified. Test bars are shaped to have a minimum of residual stress. As the cooling rate in the test bar may be quite different from that in certain sections of the casting, the designer should not assume that the test bar values duplicate those of the casting. Wherever possible, mechanical tests should be made on some of the full-size castings, preferably with loads that simulate service conditions.

Internal Soundness. Some castings fail in service because they are unsound or have shrinkage defects. Changes in gating or feeding will usually correct the unsoundness. Occasionally design must be modified to improve soundness. In the development of foundry practice on a new casting, sample castings are often examined radiographically for soundness. After proper practice has been developed, occasional radiographic examination of a production casting will suffice.

Stress Analysis. Even sound castings occasionally fail in service at loadings well below the design strength, because of residual tensile stresses. Such stresses may be evaluated by observation of brittle lacquer coatings which locate

areas of high stress and the direction of the stress, or by electrical resistance strain gages of the SR-4 type, which measure stress magnitudes. The latter technique may involve destruction of the casting, but the information obtained can lead directly to a change in design or process which will result in appreciable reduction of residual stress. It is recommended that stress distribution be studied in important load-carrying castings.

Patterns

Selection of the pattern for a given casting involves a balance between initial cost of the pattern and subsequent molding cost in the foundry, in relation to the total number of castings to be made. A loose or unmounted wood pattern is cheapest and is always used where only a few castings are required. For 50 or more castings a mounted split pattern is usually advisable, half being mounted on a matchboard; this decreases molding time and reproduces the shape more accurately. Where large quantities are involved, a pattern should be made of metal and likewise mounted on matchboards to insure long pattern life as well as dimensional accuracy of the final casting. Even when wood patterns are appropriate, both the patterns and the core boxes should be metal-faced at points where rough handling or wear is likely.

Gray Iron Castings

Gray iron usually has carbon content above 3%, primarily in the form of graphite flakes. The amount, size, shape and distribution of graphite have principal effects on the properties of the metal—especially the characteristic lack of ductility and low impact values of gray iron. However, gray iron has many favorable properties and these, together with low cost, have made it the most widely used metal for castings.

The graphite flakes improve machinability, and also make gray iron resistant to many types of wear. The stress-strain curve in the tension test is not a straight line; gray iron does not have a true modulus of elasticity. The rigidity ("modulus") is usually determined arbitrarily as the slope of the stress-strain curve at 25% of the tensile strength and in soft high-carbon irons is much lower than in the strong low-carbon irons. The modulus so evaluated may range from 8,000,000 to over 20,000,000 psi. Gray iron has high damping capacity, compared with steel, because of the graphite flakes. The soft high-carbon irons, with low modulus, have the highest damping capacity.

Gray iron has excellent castability and some thin-wall or complex designs may be produced that would not be practical in other metals. Notch effects are not so serious in gray iron as in other cast ferrous metals.

This type of iron covers a wide range of properties, depending on composition, section size and processing. Corresponding tensile strengths range from less than 20,000 to more than 60,000 psi. Yield strength (at 0.2% offset) is high; ductility, low. Compressive strength is approximately three times the tensile strength.

The relative amounts of graphite and combined carbon in cast iron depend on the cooling rate of the casting. A

composition that gives high strength in a light section may produce a soft structure high in graphite in a heavy section. Therefore, the composition should be adjusted to the size of casting. Some compositions, particularly alloy irons, vary less in mechanical properties with section size than others.

Specifications. If strength is not a factor it should not govern the choice of specification. The selection of higher strength than is needed results in higher foundry and processing costs. Alloy cast irons should not be specified where unalloyed gray iron is satisfactory.

The most popular gray iron specification is ASTM A48, which classifies irons according to minimum tensile strength; classes range from 20,000 to 60,000 psi minimum. Other ASTM specifications include: A159 (automotive); A126 (valves, flanges and pipe fittings); A74 (soil pipe and fittings); A142 (culvert pipe); A44 (water pipe); A190 (light weight and thin section); A278 (pressure-containing parts for temperatures up to 650°F); A319 (non-pressure-containing parts for elevated temperatures).

Dimensional Tolerances. For the general run of castings, dimensional tolerances approximately one-half the maximum shrinkage of the cast metal are customary. Thus, a dimensional tolerance of $\pm 1/16$ in. is common for castings about 1 ft long. Study of production operations, including the preparation of sample castings, may permit closer tolerances. Many foundries are producing gray iron castings to a tolerance of $\pm 1/32$ in. However, the purchaser should not specify closer tolerances than are required because delay and increased cost may result.

See Table I for machining allowances, which are added to normal tolerance.

Table I. Machine Finish Allowances for Gray Iron

Pattern Size, in.	Bore, in.	Finish, in.
Up to 12.....	$\frac{1}{16}$	$\frac{1}{16}$
13 to 24.....	$\frac{1}{16}$	$\frac{1}{16}$
25 to 42.....	$\frac{1}{16}$	$\frac{1}{16}$
43 to 60.....	$\frac{1}{16}$	$\frac{1}{16}$
61 to 80.....	$\frac{1}{16}$	$\frac{1}{16}$
81 to 120.....	$\frac{1}{16}$	$\frac{1}{16}$
Over 120. Special instructions required		

White Iron and Chilled Iron

White cast iron has nearly all its carbon in the combined form, as cementite (iron carbide, Fe₃C). This usually derives from low silicon content in the melt, sometimes from alloying elements.

Chilled cast iron is produced simply by casting against metal chills, which cool the iron rapidly enough to prevent the formation of graphite. The depth of the layer of chilled or white iron is controlled by adjusting silicon and carbon contents.

White iron castings are used where maximum resistance to wear is demanded. The higher the carbon content, the harder and more brittle the iron. White iron castings must be designed carefully because failures may occur in the foundry due to sharp corners and thin sections. Also, these castings are less resistant to impact loading than is gray iron. The com-

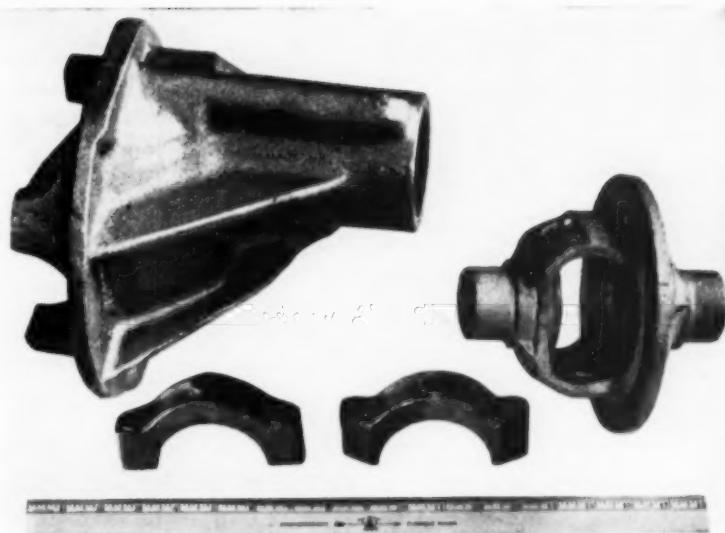


Fig. 1. Differential Case (upper left), Carrier (upper right) and Bearing Caps of Malleable Iron, Representing Good Correlation of Engineering Design and Foundry Techniques

pressive strength of white iron is usually higher than 200,000 psi.

In chilled castings the composition is such that the iron would be gray if not cooled rapidly by the chills. Consequently, the white outer portions usually have gray iron backing, and such a casting is more resistant to impact than one which is all white iron.

Typical applications for chilled iron castings are railroad car wheels, rolls, plow shares, track idlers for crawler tractors, moldboards, valve tappets and jaw crusher plates. White iron castings have more limited application. Hardness and strength of both chilled and white iron castings may be increased by alloying elements. Hardness ranges from slightly over 300 Brinell for low-carbon white iron to over 600 Brinell for high-carbon and over 600 for alloy white irons. ASTM A360 covers chilled and white iron castings. Only a few foundries produce them.

Malleable Iron Castings

In the production of malleable iron it is necessary first to produce a white iron casting of suitable composition, which is then annealed to change virtually all of the combined carbon to small particles of "temper carbon" (graphite in characteristic rounded aggregates), and to give a strong, tough casting characteristic of the ferrite matrix.

The most popular grade of malleable iron, representing the major tonnage, is designated as 32510. A higher-tensile grade is 35018, which is less frequently used and produced by only a few malleable iron foundries. Usually the engineer should confine his designs to grade 32510. ASTM A47 covers the two grades and provides test-bar properties as follows:

32510	35018
Tensile strength, min psi	50,000
Yield strength, min psi	53,000
Elongation in 2 in., min %	10
	18

These two grades are produced in air furnaces, electric furnaces or by duplex melting (cupola-to-air furnace

or cupola-to-electric furnace). Another grade, of lower tensile strength, is made in the cupola; ASTM A197 for cupola malleable iron calls for a minimum tensile strength of 40,000 psi, minimum yield of 30,000 psi and minimum elongation of 5% in 2 in. It has been used largely for fittings.

Malleable castings usually have light to medium sections, limited in thickness partly to facilitate production of iron completely white as cast. The heavier the section, the more likely is the formation of primary graphite on solidification, which will result in lower mechanical properties. The silicon content of the metal may be reduced for heavier sections but lower silicon means longer annealing cycles. Foundry defects such as hot tears and shrinks are more difficult to avoid than in gray iron because the casting is first white iron. The following design procedures will minimize foundry defects in malleable iron castings:

- 1 Provide ample fillets
- 2 Aim for uniformity of section
- 3 Taper gradually at the junction of unequal sections
- 4 Design plates in tension, ribs in compression
- 5 Provide ample section for gating and feeding
- 6 Eliminate cores where feasible
- 7 Allow sufficient pattern draft

Some of the preceding recommendations for malleable casting design are illustrated in Fig. 1 to 5. For example, Fig. 1 shows three malleable iron castings in large production—a differential case, a carrier and bearing caps. The case, at upper left, incorporates sections from $1\frac{1}{2}$ to $\frac{1}{4}$ in. thick, indicating what can be accomplished where engineering design and foundry techniques are correlated. Figure 2 is a brake support casting, practically all of which is cast in the drag. Figure 3 shows a revision in design; at the left, the ribs are in tension; in the redesign (right) the ribs are in compression and the plate in tension. Figure 4 shows an original design (left) and redesign (right) of a gear blank casting. In the original, the ribs broke in the hard iron



Fig. 2. Brake Support Casting Showing How, with Only One Center Core, a Part Can Be Designed So That Practically All of It Is Cast in the Drag

state in the foundry. The redesign eliminated this trouble.

Figure 5 shows another original design (two top pieces) and redesign (lower two). The original casting was difficult to feed and dendritic checks developed, causing breakage. The redesign provided a heavier section at the feeding point and used an H-section rather than a round one. The bent casting (bottom) illustrates toughness of the new (and lighter) design.

For castings not to be machined, size tolerance is usually $\pm 1/16$ in. per ft. Where high accuracy is required, malleable iron castings can be die straightened readily or coined, because of their ductility. If castings are straightened, one dimension and usually not more than two dimensions, can be held to $1/64$ in. In coining, tolerances of ± 0.007 to ± 0.010 in. can be held.

Usual finish allowances for machining are: milling, $1/16$ to $3/32$ in., for small castings, $1/8$ to $3/16$ in. for medium castings; reaming, $3/32$ in. on diam for cored holes under 1 in., $1/8$ to $3/16$ in. on diam for medium sizes.

Pearlitic Malleable Iron

Production of pearlitic malleable iron castings has increased greatly in the last ten years. They are used where conventional malleable iron does not have sufficient strength or wear resistance and sometimes replace steel castings or forgings. Pearlitic malleable iron has a definite amount of carbon in the matrix in the combined form. This increases hardness and strength and decreases ductility. Most pearlitic malleable iron is made by starting with the same white iron as for regular malleable and modifying the heat treatment so that the required amount of carbon is left combined. Another method is to heat treat ordinary malleable iron so as to convert some of the graphite to combined carbon. In still another system the composition is altered to leave some combined carbon after heat treatment. ASTM A220 provides for five grades (Table II).

Design problems with pearlitic are similar to those for conventional malleable. However, lower ductility makes straightening more difficult.

Nodular Iron Castings

Nodular iron, also called ductile iron and spheroidal graphite iron, was introduced in 1948. Commercial castings are being produced with sections from $1\frac{1}{8}$ to over 12 in. thick.

In producing nodular iron, a composition is selected that normally would result in a soft, weak gray cast iron.

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However, by the addition of small amounts of special alloys containing magnesium or cerium, plus special processing, the resulting casting has the carbon in spheroidal form. This usually develops high strength plus some ductility. Frequently heat treatment is required to obtain the desired properties.

ASTM A339 covers two grades:

80-60-03 60-45-10

Tensile strength, min psi .. 80,000 60,000
Yield strength, min psi 60,000 45,000
Elongation in 2 in., min psi 3.0^(a) 10

(a) Where strength is a primary requirement, the elongation requirement in grade 80-60-03 may be waived by agreement between the manufacturer and the purchaser.

Properties of grade 80-60-03 are usually obtained in the as-cast condition



Fig. 3. Revision in Design. Top and bottom views of original design are at left. Redesign, as seen from above and below, shown at right, places ribs in compression and plate in tension.

Table II. Pearlitic Malleable Irons (ASTM A220)

Grade	Min Tensile Strength, psi	Min Yield Strength, psi	Minimum Elongation in 2 in., %	Typical Brinell Hardness
43010	60,000	43,000	10	163 to 207
48005	70,000	48,000	5	179 to 228
53004	80,000	53,000	4	197 to 241
60003	80,000	60,000	3	197 to 241
70002	90,000	70,000	2	241 to 285

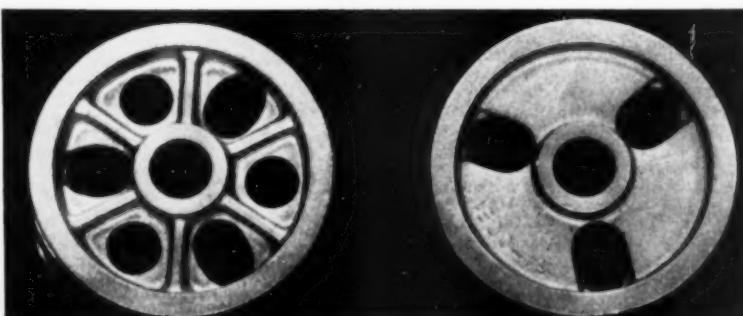


Fig. 4. Original (Left) and Redesign (Right) of a Gear Blank Casting to Overcome Cracking of Ribs While the Part Was Still in the Hard Iron State

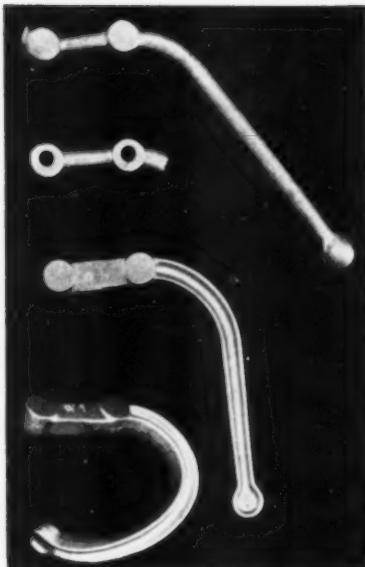


Fig. 5. Original (top two pieces) and Redesign (lower two) to Overcome Metal Feeding Problems Through a Heavier Feeding Section and Changed Section Shape. Bottom piece is bent to show toughness.

while heat treatment generally is required for grade 60-45-10. Tensile strength above 100,000 psi can be produced by oil quenching and tempering. As strength and hardness are increased, ductility is decreased. The range of properties available in nodular iron is quite similar to the range available in pearlitic malleable iron.

Usual practices of good casting design should be followed with nodular iron. Since nodular iron solidifies similarly to steel, guidance may be obtained from the principles outlined for steel. Considerably more feeding is required for nodular iron than for gray iron, if sound castings are to be obtained.

Conditions that cause hot tearing in other cast metals (such as combinations of light and heavy sections) promote high residual stresses in nodular iron. Castings of such design should be stress relieved at 900 F or higher. Chaplets should be avoided or of the light-gage variety and an effort made, by gating, to flow considerable metal through the chaplet area to insure fusion, especially for pressure castings.

Thin castings may contain primary carbide in the as-cast condition and require heating at about 1600 F to obtain ductility. This may result in warping, and subsequent straightening

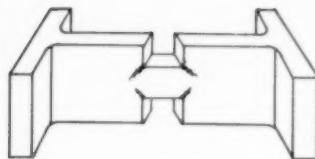


Fig. 6. Formation of Cracks or Hot Tears Resulting from Concentration of Stresses at Reduced Sections

will be necessary. The slower the cooling rate, the greater the possibility of obtaining ductility in as-cast nodular iron. Frequently sections of $\frac{1}{2}$ in. or more are required for ductility in the as-cast metal.

Most consistent uniformity of properties will be achieved in heat treated castings, and is particularly important in castings which combine widely different section thickness and may show variable properties in light and heavy sections as cast.

Dimensional tolerances are about the same as for gray iron, except on the cope surface where the machining tolerance should be 30 to 50% greater than that required for gray iron. This is because nodular iron castings have surface defects on the cope side.

When nodular iron is cast against a chill it responds similarly to gray iron by forming a hard carbide zone which is useful for wear resistance. The machinability of nodular iron is about the same as that of gray iron of the same hardness (see Fig. 3, page 50).

Nodular iron is of interest to the designer because it has good castability and a wide range of mechanical properties. At present (May 1954) relatively few foundries are supplying it.

Steel Castings

The designer should recognize four fundamental characteristics of steel as it cools from the molten state to room

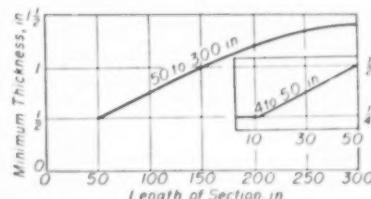


Fig. 8. Minimum Thickness of Sections of Steel Castings as a Function of Their Largest Dimension. Curve is for best design conditions wherein molten steel enters at one position on the casting and must run the lengths noted on the chart.

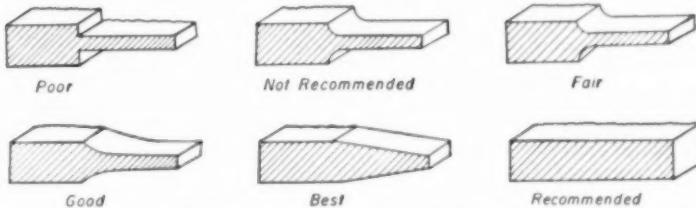


Fig. 9. Accepted Methods for Reducing or Increasing a Section. Recommended design is no change in section whenever possible. Large radii and tapered junctions are preferred to the others shown.

temperature: low fluidity, high shrinkage, low strength at 2700 F, and high cooling stresses.

Failure to meet fundamental design requirements is responsible for many defective castings. Four types of defects are typical—hot tears, shrinkage cavities, misruns and sand inclusions.

Hot tears result from wide temperature differences in castings where excessive thermal and solidification stresses result from restricted contraction and cause the metal to crack. An example is shown in Fig. 6, where contraction is restrained by rammed sand between the flanges. Stress concentrates at the reduced section and hot tears may form at the re-entrant angles. A uniform section between the flanges would distribute the stress uniformly.

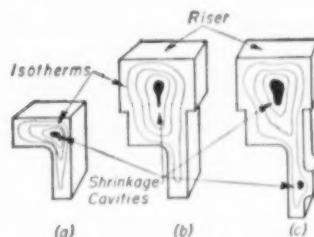


Fig. 7. Within Limits, Risers Can Help to Overcome Shrinkage Cavities. Manner in which the casting solidifies is shown by isotherms in the casting and riser. Heavy section at the boss in (c) cannot be fed through the lighter section above.

Shrinkage cavities are caused by lack of metal to fill the space resulting from volumetric contraction during solidification. This defect is found in sections that, because of poor design, must be fed through thinner sections, which solidify before the thicker sections are filled.

Risers are not always effective; for instance, in Fig. 7, section (a) would have a shrinkage cavity at the position shown if it were not fed by a riser as shown in sketch (b). The boss in sketch (c) contains a shrinkage cavity because the riser will not feed a heavy section through a lighter section.

Long, thin mold sections should be avoided, if possible, lest "misruns" (incomplete filling of the section) occur.

The complicated nature of some parts results in difficult mold preparation.

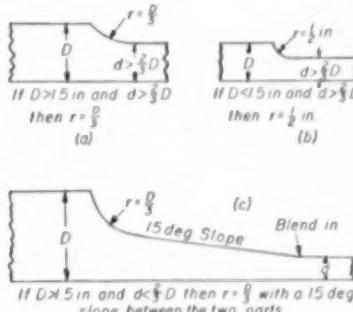


Fig. 10. Section Changes May Be Made on One Side Only. Values cited are recommended design ratios.

The flow of molten steel may break off portions of the mold or core walls and entrap sand in the casting (inclusions).

Elements of Design. Although the skilled foundryman may be able to furnish sound and serviceable steel castings from poor designs, it will be at a higher price than for equivalent results with good design.

Usually design is based on yield strength, with a factor of safety from 3 to 10. Factors of safety are often factors of ignorance; there is a real need to determine actual stresses in the laboratory and under service conditions.

Thin sections often may seem satisfactory from calculations of strength and rigidity, but the low fluidity of molten steel must be considered too. A minimum thickness of $\frac{1}{4}$ in. is usu-

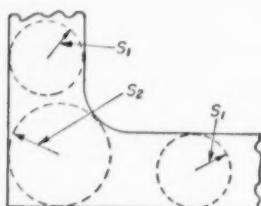


Fig. 11. Position of Hot Spots at Junction of Two Arms of Same Thickness Shown by the Method of Inscribed Circles

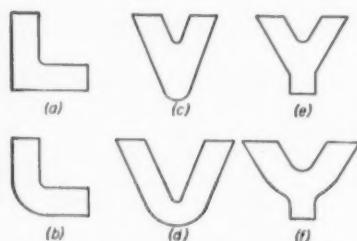


Fig. 12. Examples of Modification in Design. Bottom designs, (b), (d) and (f), are recommended because sections at the junctions are slightly smaller than the arms.

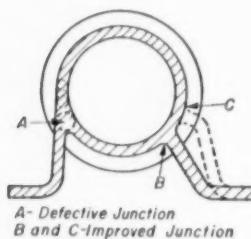


Fig. 13. Cross Section of a Motor Frame Steel Casting, with Three Types of Section Junctions. Too much metal is present at A.

Table III. Dimensional Tolerances for Steel Castings Not to Be Machined

	Dimension to Which Tolerance Applies		
	Under 12 in. ^(a)	12 to 36 in.	36 to 120 in.
Average	$0.06 + 0.006 D$	$0.06 + 0.006 D$	$0.08 + 0.006 D$
Concise	$0.04 + 0.005 D$	$0.05 + 0.005 D$	$0.07 + 0.005 D$
Minimum	$0.03 + 0.004 D$	$0.04 + 0.004 D$	$0.06 + 0.004 D$

(a) Tolerance $\frac{1}{8}$ in. min. D is the longest dimension of the casting in inches

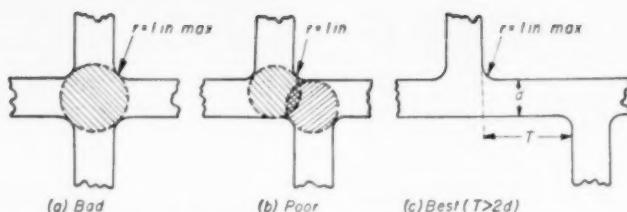


Fig. 14. Mass of Metal at Junctions in (a) and (b). Rule Out the Design in Favor of (c) Where Offset Is at Least Twice the Arm Thickness.

ally recommended. For a given thickness, steel flows better in a narrow web than in a wide one. If the $\frac{1}{4}$ -in. section is longer than 12 in., the minimum thickness should be increased as indicated in Fig. 8.

Uniformity of section minimizes hot spots which are responsible for temperature gradients, uneven contractions, shrinkage cavities (in inaccessible locations), residual stresses and often hot tears. Figure 9 indicates two satisfactory methods of reducing or increasing a section. Another way is to make the transition entirely on one side (Fig. 10). Shrinkage and cracks caused by isolated hot spots are illustrated by Fig. 11; with the two arms of the same thickness, there will be a "hot spot" at the junction. An improved design is shown in (b) of Fig. 12. This sketch also shows two other modifications which improve design through elimination of possible hot spots.

The mass of metal at junctions should be reduced as much as possible (Fig. 13 and 14). Increasing section thickness to increase strength may result in defects from excessive mass. Figure 15 indicates one method of modifying a design to eliminate the heavier section.

Sand cores surrounded by large masses of metal may fuse and adhere to the metal, causing difficulty in cleaning. The minimum diameter of the core will depend on the mass of steel surrounding it and the length of the cored area, and consultation between designer and foundryman is especially desirable.

Dimensional Tolerances. A guide to tolerances on size of castings that are not to be machined is shown in Table III. The average values are recommended; the minimums should be respected. The allowance to be added for machining will depend on the design of the castings; however, Table IV is a guide.

Specifications. ASTM A27 covers a large volume of commercial castings from mild to medium-strength carbon steel for general application. It covers eight grades of steel with maximum carbon ranging from 0.25 to 0.35%. Where tensile properties are included in the specification the range of minimum tensile strength is from 60,000 to 70,000 psi, with yield strength 30,000 to 36,000 psi, minimum elongation 20 to

Table IV. Machine Finish Allowances for Steel Castings

Diameter, in.	Allowance on Radius, in.
Outside Radii on Circular Castings^(a)	
Up to 18	$\frac{1}{4}$
18 to 36	$\frac{1}{8}$
36 to 48	$\frac{3}{8}$
48 to 72	$\frac{1}{2}$
72 to 108	$\frac{5}{8}$
Bore Radii on Holes	
Up to 1	Solid
2 to 7	$\frac{1}{4}$
7 to 12	$\frac{3}{8}$
12 to 20	$\frac{1}{2}$

(a) Rings, spoked wheels, spoked gears and other circular castings

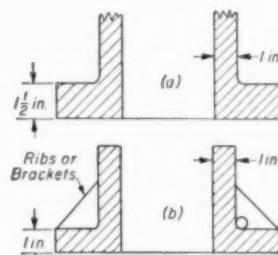


Fig. 15. Ribs or Brackets Permit Uniform Section and Avoid Defects.

24%, and minimum reduction of area 30 to 35%.

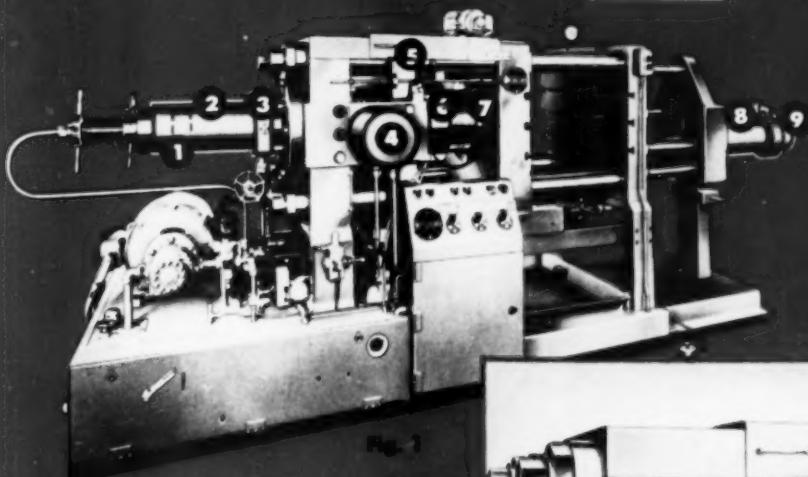
Other common ASTM specifications for steel castings include: A95 (valves, flanges and fittings at high temperature); A216 (fusion welded castings at high temperature); A356 (steam turbines); A217 (alloy castings for pressure-containing parts at high temperature); A352 (ferritic castings for pressure containing parts at high temperature); A148 (high-strength castings for structural purposes); and A128 (austenitic manganese steel).

References

Illustrations and many of the data given here have been published in the following manuals, which may be consulted for further specific information:

- Cast Metals Handbook, American Foundrymen's Society, Chicago
- Engineering Properties of Cast Iron, American Foundrymen's Society, Chicago
- Symposium on Casting Design, 1952, Foundry Educational Foundation, Cleveland
- Steel Castings Handbook, Steel Founders' Society of America, Cleveland
- American Malleable Iron, Malleable Founders' Society, Cleveland
- Various publications of the Gray Iron Founders' Society, Cleveland

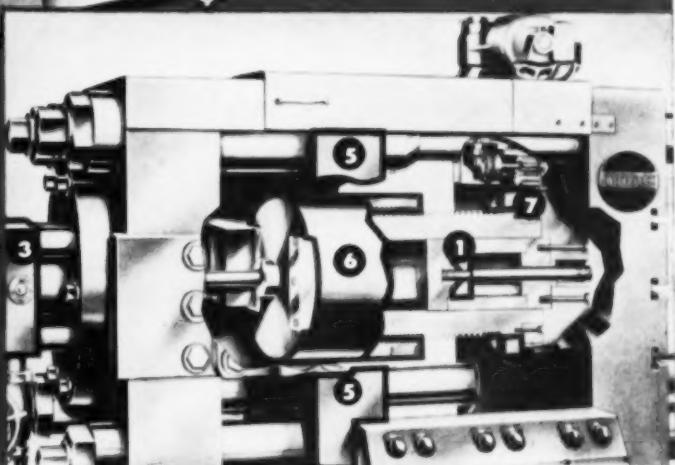
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- 4 CYLINDER SLEEVE
- 5 PLATEN
- 6 ADJUSTING NUT
- 7 RETAINING RING
- 8 CYLINDER SLEEVE
- 9 CYLINDER HEAD

Fig. 1
Fig. 2

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-459.4 to 0		0 to 100				100 to 1000				1000 to 2000				2000 to 3000				
C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	C	F	
-273	-459.4	0	32	10.0	50	122.0	38	100	212	260	500	932	538	1000	1832	816	1500	
-268	-450	1	33.8	10.6	51	123.8	43	110	226	266	510	950	543	1010	1850	821	1510	
-262	-440	2	35.6	11.1	52	125.6	49	120	248	271	520	968	549	1020	1868	827	1520	
-257	-430	3	37.4	11.7	53	127.4	54	130	266	277	530	986	554	1030	1886	832	1530	
-251	-420	4	39.2	12.2	54	129.2	60	140	284	282	540	1004	560	1040	1904	838	1540	
-246	-410	5	41.0	12.8	56	131.8	66	150	302	288	550	1020	566	1050	1922	843	1560	
-240	-400	6	42.8	13.3	56	132.8	71	160	320	293	560	1040	571	1160	1940	849	1570	
-234	-390	7	44.6	13.9	57	134.6	77	170	338	299	570	1058	577	1070	1958	854	1580	
-229	-380	8	46.4	14.4	58	136.4	82	180	356	304	580	1076	582	1080	1976	860	1590	
-223	-370	9	48.2	15.0	59	138.2	88	190	374	310	590	1094	588	1090	1994	866	1590	
-218	-360	10	50.0	15.6	60	140.0	93	200	392	316	600	1112	593	1100	2012	871	1600	
-212	-350	11	51.8	16.1	61	141.8	99	210	410	321	610	1130	599	1110	2030	877	1610	
-207	-340	12	53.6	16.7	62	143.6	100	212	413.6	327	620	1148	604	1120	2048	882	1620	
-201	-330	13	55.4	17.2	63	145.4	104	220	428	332	630	1150	606	1130	2066	888	1630	
-196	-320	14	57.2	17.8	64	147.2	110	230	446	338	640	1164	616	1140	2084	893	1640	
-190	-310	15	59.0	18.3	65	149.0	116	240	464	343	650	1203	621	1150	2102	899	1650	
-184	-300	16	60.8	18.9	66	150.8	121	250	482	349	660	1220	627	1160	2120	904	1660	
-179	-290	17	62.6	19.4	67	152.6	127	260	500	354	670	1238	632	1170	2138	910	1670	
-173	-280	18	64.4	20.0	68	154.4	132	270	518	360	680	1256	638	1180	2156	916	1680	
-169	-273	19	66.2	20.6	69	156.2	138	280	536	366	690	1274	643	1190	2174	921	1690	
-163	-270	20	68.0	21.1	70	158.0	143	290	554	371	700	1292	649	1200	2192	927	1700	
-162	-260	21	69.8	21.7	71	159.8	149	300	572	377	710	1310	654	1210	2210	932	1710	
-157	-250	22	71.6	22.2	72	161.6	154	310	590	382	720	1328	660	1220	2228	938	1720	
-151	-240	23	73.4	22.8	73	163.4	160	320	608	388	730	1346	666	1230	2246	943	1730	
-146	-230	24	75.2	23.3	74	165.2	166	330	626	393	740	1364	671	1240	2264	949	1740	
-140	-220	25	77.0	23.9	75	167.0	171	340	644	399	750	1382	677	1250	2282	954	1750	
-134	-210	26	78.8	24.4	76	168.8	177	350	662	404	760	1400	682	1260	2300	960	1760	
-129	-200	27	80.6	25.0	77	170.6	182	360	680	410	770	1418	688	1270	2318	966	1770	
-123	-190	28	82.4	25.6	78	172.4	188	370	698	416	780	1436	693	1280	2336	971	1780	
-118	-180	29	84.2	26.1	79	174.2	193	380	716	421	790	1454	699	1290	2354	977	1790	
-112	-170	30	86.0	26.7	80	176.0	199	390	734	427	800	1472	704	1300	2372	982	1800	
-107	-160	31	87.8	27.2	82	177.8	204	400	752	432	810	1490	710	1310	2390	988	1810	
-101	-150	32	89.6	27.8	82	179.6	210	410	770	438	820	1508	716	1320	2408	993	1820	
-96	-140	33	91.4	28.3	83	181.4	216	420	788	443	830	1526	721	1330	2426	999	1830	
-90	-130	202	1.1	93.2	28.9	84	183.2	221	430	806	449	840	1544	727	1340	2444	1004	1840
-84	-120	1.2	95.0	29.4	85	185.0	227	440	824	454	850	1562	732	1350	2462	1010	1850	
-79	-110	1.3	96.8	30.0	86	186.8	232	450	842	460	860	1580	738	1360	2480	1016	1860	
-73	-100	1.4	98.6	30.6	87	188.6	238	460	860	466	870	1598	743	1370	2498	1021	1870	
-68	-90	1.5	100.4	31.2	88	190.4	243	470	878	471	880	1616	749	1380	2516	1027	1880	
-62	-80	1.6	102.2	31.7	89	192.2	249	480	886	477	890	1634	754	1390	2534	1032	1890	
-57	-70	1.7	104.0	32.2	90	194.0	254	490	914	482	900	1652	760	1400	2552	1038	1900	
-51	-60	1.8	105.8	32.8	91	195.8	260	500	930	488	910	1670	766	1410	2570	1043	1910	
-46	-50	1.9	107.6	33.3	92	197.6	266	510	943	493	920	1688	771	1420	2588	1049	1920	
-40	-40	2.0	109.4	33.9	93	199.4	272	520	949	499	930	1706	777	1430	2606	1054	1930	
-34	-30	2.1	111.2	34.4	94	201.2	277	530	954	504	940	1724	782	1440	2624	1060	1940	
-29	-20	2.2	113.0	35.0	95	203.8	283	540	960	510	950	1742	788	1452	2642	1066	1950	
-23	-10	2.3	114.8	35.6	96	204.8	289	546	966	516	960	1760	793	1460	2660	1071	1959	
-17.8	0	32	116.6	36.1	97	206.6	295	552	971	521	970	1778	799	1470	2678	1077	1960	
-17	9.4	49	118.4	36.7	98	208.4	301	557	976	527	980	1796	804	1480	2696	1082	1966	
-17	9.4	49	120.2	37.2	99	210.2	307	562	981	532	990	1814	810	1490	2714	1088	1972	
												538	1000	1832		1093	2000	

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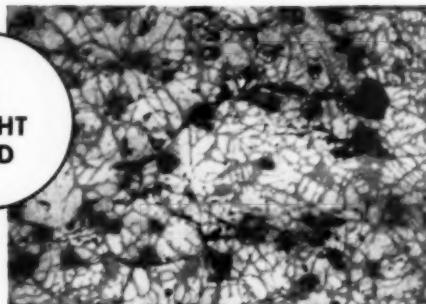
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Design of Brazed Joints

By the ASM Committee on Brazed Joints

THE MOST IMPORTANT factors in the design of brazed joints are dealt with here. Detailed discussion is limited largely to copper and silver brazing. Brazing processes are examined only briefly, in relation to some of the principal design considerations.

The American Welding Society has defined "brazing" as "a group of welding processes wherein coalescence is produced by heating to suitable temperatures above 800 F and by using a nonferrous filler metal having a melting point below that of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction." This definition excludes braze welding (sometimes called bronze welding), in which a filler metal having a melting point below that of the base metal, and above 800 F, is fed into a fillet, groove or slot but is *not* distributed in the joint by capillary attraction.

There has been some disagreement as to the classification of joints in which a thin shim of the filler metal is placed between the closely fitted joint surfaces, covering all or approximately all of the area, with the joint members clamped or pressed together during heating. There is no flow of the filler metal by capillary attraction in the usual acceptance of the term, but joint design is the same as for brazing, rather than for braze welding.

Types of Joints

The types of brazed joints generally used are lap and butt or modifications and combinations of them. All require that joint faces be kept at a close and uniform distance apart to insure good capillary attraction during brazing. As

Subdivision	Page
Types of Joints	115
Filler Metals	
and Base Metals	115
Joint Clearance	116
Strength of Brazed Joints	117
Stress Distribution	118
Fatigue Strength	119
Impact Strength	120
Elevated and Sub-Zero Temperatures	120
Electrical Conductivity	120
Corrosion Resistance	121
Brazing Processes	121

a result, the filler metal in brazed joints has the physical structure of a thin casting firmly joined to the base metals, regardless of its form when applied to the joint.

Lap (Shear) Joints are preferred when the extra thickness caused by the lap is not objectionable. Lap joints also facilitate the alignment of pipes, fittings and tubular members. A lap three times the thickness of the weakest member will usually provide joint strength equivalent to that of the parts joined. Figure 1 shows three lap joints of correct design.

Butt Joints are used where lap joints are undesirable or impractical because of space considerations or appearance. A properly designed butt joint is shown in Fig. 2(a). Two poorly fitted joints that depend on an excessive amount of filler metal and a bead on the surface of the joint members, respectively, to counteract poor fitting are shown in

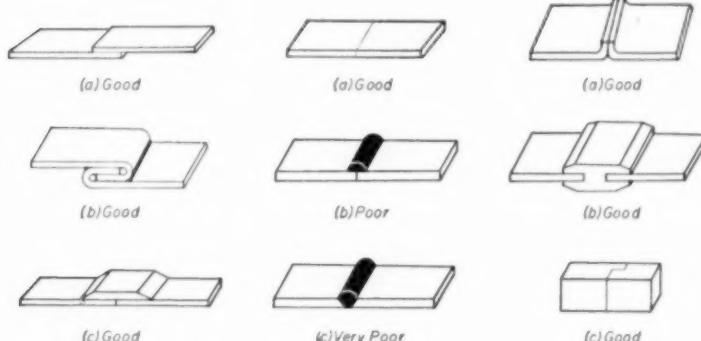


Fig. 1. (Above Left) Brazed Lap Joints. Three examples of good design practice

Fig. 2. (Above Center) Brazed Butt Joints. Examples of one good and two poor designs

Fig. 3. (Column of Line Drawings at Right) Modified Lap and Butt Joints Common in Design Practice. (a) Good modified butt joint. (b) and (c) Good modified butt-lap joints. (d) Good modified lap joint. (e) Poor modified butt joint

Fig. 2(b) and (c). Other modified butt joints are shown in Fig. 3.

Scarf Joints are modified butt joints and are used to provide a greater surface area than a 90-deg cut where the double thickness of the lap joint is prohibitive (Fig. 4). If the angle of the



Fig. 4. Scarf Joint

scarf with the longitudinal axis is reduced to 30 deg, the area on the joint face will be two times, and at 19½ deg will be three times the area of a right angle section. Scarf joints carefully prepared with parallel joint faces are useful in joining band saws or in similar applications where bending as well as tension occurs. Other good and poor joints are illustrated in Fig. 5.

Method of Introducing Metals into the joint depends on the manner of heating, the design of joint and the quantity to be produced. In general, filler metal may be either face-fed or preplaced into all types of joints. With flat members, a light pressure can be applied during brazing to hold them in proper relation. In face feeding, filler metal in the form of wire, rod or strip is fed by hand into the joint area when the temperature is proper to flow the filler metal. Preplaced filler metal (wire, rings, special shapes, shims, filings or washers) is inserted when the parts are assembled, after they have been cleaned and fluxed. When brazing temperature is reached, the preplaced filler metal melts and flows into the joint area. The preplaced form should be located so that it does not interfere with the fit of mating parts.

Most of the typical joints shown in Fig. 1 through 5 could be made either by face feeding or preplacement of the filler metal. The joints in Fig. 6 illustrate common examples of preplacement of wire, washers and shims; poor design that prevents the upper member from settling on the lower as the filler alloy melts is shown in Fig. 6(a); the examples in (b) and (c) are satisfactory; (d) and (e) show voids left after brazing when rings of filler metal are preplaced in grooves; such voids reduce the bonded lap area and may necessitate an increase in the length of lap. However, the filler metal should be placed so that, during brazing, the flux will be forced out of the joint ahead of the filler metal as shown in 6(f) and (g); examples (h) and (i) represent other commonly used methods of placing preformed filler metal.

Joints in fully enclosed vessels must provide a vent for escape of expanding gases. This applies also to the joining of parts with included pockets—for example, a square-ended rod in a blind hole.

Filler Metals and Base Metals

Filler metals are divided into seven groups, according to chemical composition, as shown in Table I.



Supplements the article on pages 78 to 81 of the 1948 ASM Metals Handbook.

Table I. Chemical Compositions of Brazing Filler Metals
(Single values are maximum percentages, except where otherwise noted.)

AWS-ASTM Class	Si	Cu	Fe	Zn	Mg	Mn	Cr	Ti	Al	Others
										Each Total
Aluminum-Silicon										
BAlSi-1	4.0-6.0	0.30	0.80	0.10	0.05	0.05	....	0.20	Rem	0.05 0.15
BAlSi-2	6.8-8.2	0.25	0.80	0.20	....	....	....	....	Rem	0.05 0.15
BAlSi-3	9.3-10.7	3.3-4.7	0.80	0.20	0.15	0.15	0.15	....	Rem	0.05 0.15
BAlSi-4	11.0-13.0	0.30	0.80	0.20	0.10	0.15	....	....	Rem	0.05 0.15
P										
Copper-Phosphorus										
BCuP-1	....	4.75 to 5.25	....	....	....	....	....	....	Rem	0.15
BCuP-2	....	6.75 to 7.50	....	....	....	....	....	....	Rem	0.15
BCuP-3	....	6.00 to 6.50	....	4.75 to 5.25	....	....	....	....	Rem	0.15
BCuP-4	....	6.75 to 7.80	....	5.75 to 6.25	....	....	....	....	Rem	0.15
BCuP-5	....	4.75 to 5.25	....	14.50 to 15.50	....	....	....	....	Rem	0.15
Ag										
Cu										
Zn										
Cd										
Ni										
Sn										
Others										
Silver										
BAg-1	44 to 46	14 to 16	14 to 18	23 to 25	....	....	....	....	....	0.15
BAg-2	34 to 36	25 to 27	19 to 23	17 to 19	....	....	....	....	....	0.15
BAg-3	49 to 51	14.5 to 16.5	13.5 to 17.5	15 to 17	2.5 to 3.5	....	....	....	....	0.15
BAg-4	39 to 41	29 to 31	26 to 30	....	1.5 to 2.5	....	....	....	....	0.15
BAg-5	44 to 46	29 to 31	23 to 27	....	....	....	....	....	....	0.15
BAg-6	49 to 51	33 to 35	14 to 18	....	....	....	....	....	....	0.15
BAg-7	55 to 57	21 to 23	15 to 19	....	....	....	....	....	4.5 to 5.5	0.15
BAg-8	71 to 73	27 to 29	....	....	....	....	....	....	....	0.15
BAg-9	64 to 66	19 to 21	13 to 17	....	....	....	....	....	....	0.15
BAg-10	69 to 71	19 to 21	8 to 12	....	....	....	....	....	....	0.15
BAg-11	74 to 76	21 to 23	2.5 to 3.5	....	....	....	....	....	....	0.15
Au										
Cu										
Copper-Gold										
BCuAu-1	....	37.25 to 37.75	....	....	....	....	....	....	Rem	0.005
BCuAu-2	....	79.75 to 80.25	....	....	....	....	....	....	Rem	0.005
Cu										
Sn										
Fe										
Mn										
Ni										
P										
Pb										
Al										
Mn										
Zn										
Si										
Cu										
Ni										
Mg										
Others										
Copper and Copper-Zinc										
BCu	99.90 min ^(a)	....	....	....	0.075	0.02	0.01	....	....	0.10
BCuZn-1	58.0-62.0	....	....	....	....	0.05	0.01	....	....	Rem 0.50
BCuZn-2	57.0 min	0.25-	....	....	....	0.05	0.01	....	....	Rem 0.50
		1.0	....	....	....	....	....	....	....	....
BCuZn-3 ^(b)	56.0 min	1.1	0.25-	1.0	1.0	....	0.05	0.01	0.25	....
			1.25	....	....	....	....	....	....	Rem 0.50
BCuZn-4	50.0-55.0	....	0.10	....	....	....	0.50	....	....	Rem 0.50
BCuZn-5	50.0-53.0	3.0-	0.10	....	....	....	0.50	....	....	Rem 0.50
		4.5	....	....	....	....	....	....	....	....
BCuZn-6	46.0-50.0	....	0.25	....	9.0-	....	0.05	0.005	0.15	....
			11.0	....	....	....	....	....	....	Rem 0.50
BCuZn-7	46.0-48.0	....	....	....	10.0-	0.20-	....	....	0.15	0.30-
			11.0	0.50	....	....	....	....	1.00	....
Heat-Resisting Metals										
BNiCr	65 to 75	13 to 20	2.75 to 4.75	(e)	(e)	(e)	....	....	....	0.50
BAGMn	....	....	....	....	....	....	84 to 86	14 to 16	....	0.15

(a) Copper plus silver. (b) RCuZn-B and RCuZn-C welding rods (see Tentative Specifications for Copper and Copper-Alloy Welding Rods) (ASTM B259; AWS A5.7) meet these requirements. BCuZn-3 brazing filler metal can be used as RCuZn-B or RCuZn-C welding rod only if it meets the specification requirements of these rods.

(c) Total iron plus silicon plus carbon = 10.0 max

Selection of the base metal depends, as always, on the service requirements.

The problems may involve joining dissimilar metals, such as brass to steel, or light and heavy sections of the same metal.

Except for magnesium, more than one filler metal can be used with each base metal. Selection depends on the composition and properties of the base metal, corrosion resistance, method of heating and the effects of brazing temperature on properties of the base metal.

The method of heating is important in selecting a filler metal. In slow furnace heating, especially of massive

parts, a filler alloy approaching a eutectic composition (narrow melting range) is best. When large gaps must be filled, or fillets are required, alloys having a wide temperature range between the solidus and liquidus temperatures are best. Brazing fillers which contain phosphorus are self-fluxing on copper and copper alloys, but are not used on ferrous alloys or on other metals containing more than 10% Ni, because brittle phosphides are formed.

The same general principles on method of heating apply to brass and silver filler metals, except for the higher brazing temperatures of the brasses.

ASM Committee on Braze Joints

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Joint Clearance

Small clearances give the benefit of capillary attraction to flow the filler metal. Clearances recommended by the AWS-ASTM Joint Committee on Filler Metal in ASTM Specification B260-52T are listed in Table II.

As joint clearances cannot be measured conveniently at brazing temperature, the designer must compute them, allowing for the effects of expansion on heating the parts from room tempera-

Table II. Recommended Clearance at Brazing Temperatures (AWS-ASTM)

Filler Metal Group	Joint Clearance, in. ^(a)
Aluminum-Silicon	0.006 to 0.010 ^(b) 0.010 to 0.025 ^(c)
Copper-Phosphorus	0.001 to 0.005
Silver	0.002 to 0.005
Copper-Gold	0.002 to 0.005
Copper	0.000 to 0.002 ^(d)
Copper-Zinc	0.002 to 0.005
Magnesium	0.004 to 0.010
Nickel-Chromium	0.002 to 0.005
Silver-Manganese	0.002 to 0.005

(a) For round or tubular members this means a clearance on the radius. (b) Length of lap less than $\frac{1}{4}$ in. (c) Length of lap more than $\frac{1}{4}$ in. (d) For maximum strength use 0.000 clearance, or press fit

ture to the brazing temperature (see Table III). If a brass tube is braze into a carbon steel tube, the brass will expand much more than the steel and therefore will close some or all of the space provided at room temperature. The space might be too small for the filler metal to flow or, if it did flow, the contraction of the brass on cooling might pull it away from the steel. Unless the filler metal is thick enough to withstand this stretching action, it will crack. The contrary effect would occur if the steel were braze inside the brass tube; thus, a very small original clearance would be needed and, after cooling, the filler metal would be in compression, which is the most desirable condition to prevent cracking during cooling of the joint.

Even when joint members are made of the same metal they may differ enough in shape or size to heat and cool nonuniformly, which may cause cracking on cooling unless enough thickness of filler metal is provided. Long butt joints are an example of the difficulty of uniform heating and cooling.

Heat treatment, especially quenching, after brazing may crack joints between members of different size and shape.

The smaller parts will cool faster and may cause thermal stresses higher than the strength of the filler metal, particularly when the filler metal is still in the hot short temperature range while these stresses develop. The clearances in Table II are usually sufficient to prevent such heating and cooling effects.

Another example requiring special consideration is the joining of a long section of a brittle member, such as sintered carbide, to steel. As the assembly cools, the steel contracts unevenly because the side bonded to the rigid

carbide is restrained; the stresses may either break the bond or crack the carbide. Brazing a thin sheet of copper between carbide and steel will prevent the cracking; the soft copper absorbs most of the strain.

The wide clearances with aluminum filler metals (0.006 to 0.025 in.) are required to maintain good capillary flow because the aluminum-silicon filler metal is viscous and alloys rapidly with the joint members at brazing heat.

For copper, desirable clearances are very small or negative (0.000 ± 0.002 in.)

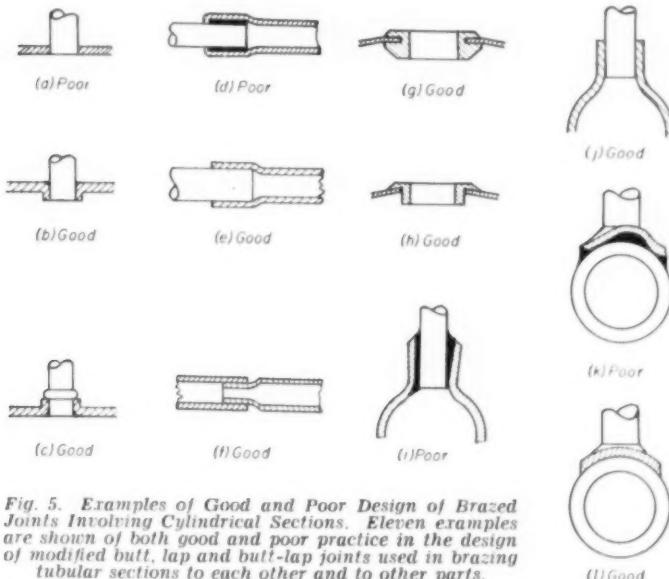


Fig. 5. Examples of Good and Poor Design of Braze Joints Involving Cylindrical Sections. Eleven examples are shown of both good and poor practice in the design of modified butt, lap and butt-lap joints used in brazing tubular sections to each other and to other parts.

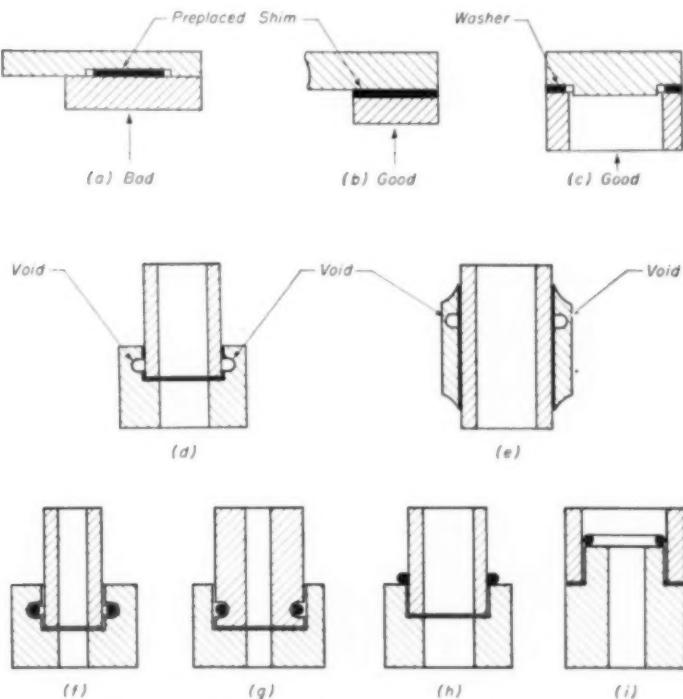


Fig. 6. Joints Braze with Preplaced Filler Metal Forms

because the filler metal is less viscous and alloys less rapidly. Figure 7 shows that a "press fit" gives no appreciable gain in strength over a "snug fit" (0.000 allowance). In addition, drive fits require a longer heating time to allow the copper to penetrate the joint and they create stress concentration that may reduce the service life of parts subjected to repeated cycles of stress.

Figure 8 shows that, under the test conditions, with small clearances and base metal of high strength, the joint strength greatly exceeds that of the filler metal, probably because the necking tendency of the filler metal is prevented. When the metal being joined is weaker than the filler metal, this effect will not occur. These tests relate to tensile strength of butt joints; the effect of joint clearance may be less for shear strength of lap joints.

For silver brazing of low-carbon steel, the peak is not so sharp as in Fig. 8, depending on the strength of the steel.

Strength of Braze Joints

When several members of different dimensions are joined by brazing, the design of the assembly will often have a pronounced effect on the combination of stresses.

Strength of Filler Metals. The tensile

Table III. Solidus, Liquidus, and Braze Temperature Ranges of Braze Filler Metals

AWS-ASTM Class	Solidus, deg Fahr	Liquidus, deg Fahr	Braze Temperature Range, deg Fahr
Aluminum-Silicon			
BAISi-1	1070	1165	1150 to 1185
BAISi-2	1070	1135	1120 to 1140
BAISi-3	970	1085	1050 to 1185
BAISi-4	1070	1080	1090 to 1185
Copper-Phosphorus			
BCuP-1	1305	1650	1450 to 1700
BCuP-2	1305	1485	1350 to 1550
BCuP-3	1195	1500	1300 to 1550
BCuP-4	1185	1380	1300 to 1500
BCuP-5	1185	1500	1300 to 1500
Silver			
BAG-1	1125	1145	1145 to 1400
BAG-2	1125	1295	1295 to 1550
BAG-3	1195	1275	1270 to 1500
BAG-4	1240	1435	1435 to 1650
BAG-5	1250	1370	1370 to 1550
BAG-6	1270	1425	1425 to 1600
BAG-7	1145	1295	1205 to 1400
BAG-8	1435	1435	1435 to 1650
BAG-9	1280	1325	1325 to 1550
BAG-10	1335	1390	1390 to 1600
BAG-11	1305	1450	1450 to 1650
Copper-Gold			
BCuAu-1	1755	1815	1815 to 2000
BCuAu-2	1620	1630	1630 to 1850
Copper and Copper-Zinc			
BCu	1980	1930	2000 to 2100
BCuZn-1	1650	1660	1670 to 1750
BCuZn-2	1630	1650	1670 to 1750
BCuZn-3	1590	1630	1670 to 1750
BCuZn-4	1570	1595	1600 to 1700
BCuZn-5	1585	1610	1620 to 1700
BCuZn-6	1690	1715	1720 to 1800
BCuZn-7	1635	1710	1690 to 1800
Magnesium			
BMg	770	1110	1120 to 1160
Heat-Resistant			
BNiCr	1850	1950	2000 to 2150
BAgMn	1760	1780	1780 to 2100

Solidus and liquidus shown are for the nominal composition in each classification.

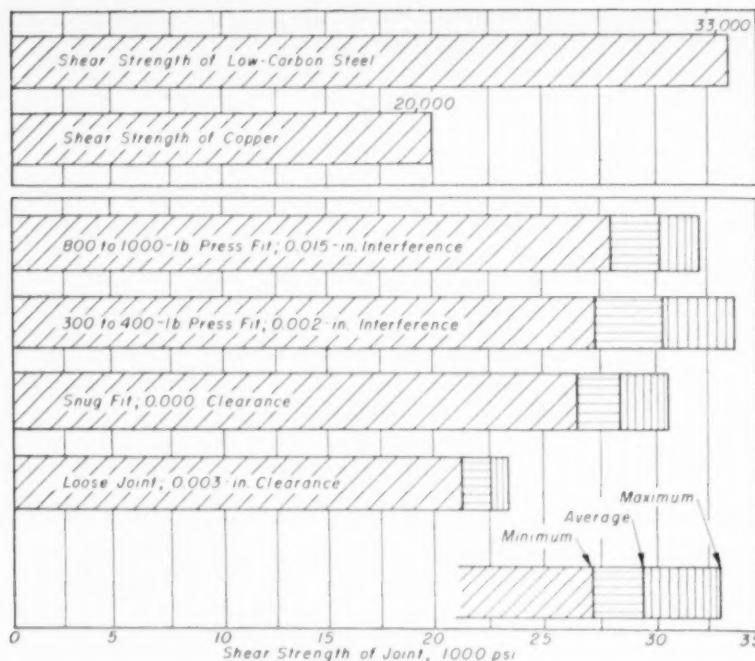


Fig. 7. Effect of Fit on the Shear Strength of Copper Braze Joints in Low-Carbon Steels (Oswald and Homan)

and shear strengths of the filler metal are of secondary importance in determining the strength of the joint. When the filler metal is stronger than the base metal, failure will occur outside the joint; when the joint members have much higher tensile strength than the filler metal, failure will be in the joint but usually at a stress much higher than the tensile strength of the filler metal itself if the joint has been fitted with recommended clearance (Table II) and properly brazed.

Strength of Joints. With silver brazing alloy of tensile strength 60,000 to 70,000 psi, the tensile strength of a wiped joint* in stainless steel may sometimes be as high as 130,000 psi, with an average of 80,000 to 100,000 psi for the usual range of clearances, as shown in Fig. 8.

Strength of joints made with silver brazing alloys on metals of lower strength than the brazing alloy will be no stronger than the metals brazed, as shown in Fig. 9.

Figure 10, for wiped silver braze joints, shows less percentage variation in shear strength with different base metals than for silver braze butt joints in tension (Fig. 9). The results in Fig. 10 are for specimens loaded in pure shear, uncombined with tension stresses as normally found in lap joints; note also that the results are plotted against

*Wiped joints of high quality are made by rubbing the joint faces together before the filler metal freezes.

tensile strength and not shear strength of the base metal. Higher shear strength values may be realized in the thicker silver braze joints on stronger base metals, while thinner joints give higher values on the weaker base metals, although differences are small. A conservative maximum value of 25,000 psi in shear for silver alloy filler metal is recommended for design.

Joints made with BCu copper brazing alloys, whose shear strength is about 20,000 psi, approach the shear strength of the base metal, depending on the clearances, as shown in Fig. 7.

Table IV summarizes the available data on shear and tensile strengths of the most common combinations of filler metal and base metal.

Data on brazing various aluminum alloy products are given on page 784 of the 1948 Metals Handbook.

Stress Distribution

Stress concentration is likely to be serious when the joint members are stronger than the brazing alloy and differ in thickness and rigidity. Figure 11 illustrates the problem. If a rigid handle is brazed to the thin blade of a mason's trowel, as shown in Fig. 11(a), and the blade is bent, it starts to tear at the end of the handle as shown in Fig. 11(b). No strength is gained by increasing the length of the joint; the point of high stress is only moved farther along the blade.

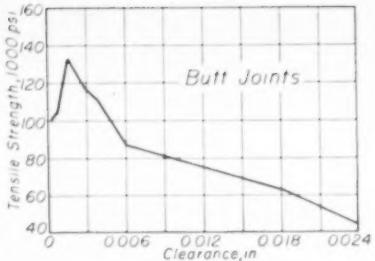


Fig. 8. Relation of Tensile Strength of Brazed Joint to Thickness of Filler Metal in Joining 0.031 in. 18-8 Stainless Steel of 160,000 psi Tensile Strength with Filler Metal of 65,000 psi (Ref. 17)

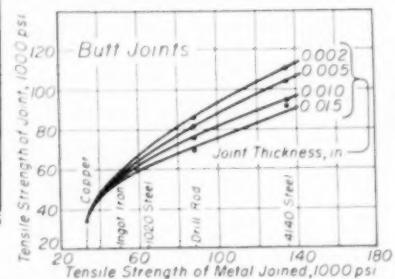


Fig. 9. Relation of Joint Tensile Strength with Tensile Strength of Metal Joined at Various Thicknesses of Filler Metal (Ref. 17)

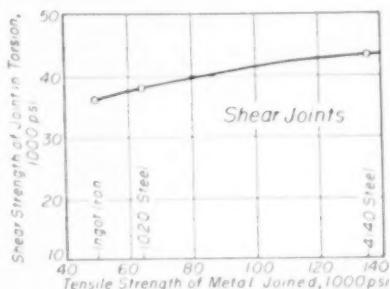


Fig. 10. Relation of Shear Strength of Silver Braze Joints in Torsion to Tensile Strength of Metal Joined. Joint clearances in these tests on wiped joints varied from 0.001 to 0.004 in. (Ref. 17)

One way to eliminate this stress concentration is to taper the rigid member as shown in Fig. 11(c), (d) and (e). Another solution is shown in Fig. 11(f), where the flexible member is thickened. Tapering is preferable, however.

Distribution of Shear Stress in Lap Joints. Figure 12(a) illustrates a simple lap joint with marks scribed on the brazing layer. After the load is applied

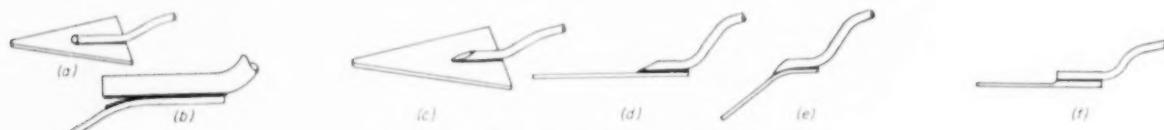


Fig. 11. Stress Concentration in a Braze Joint

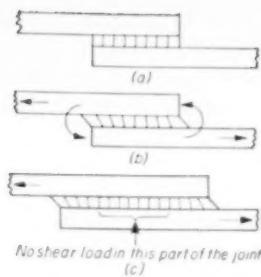


Fig. 12. Analysis of Stresses in a Brazed Joint

as shown in Fig. 12(b) these marks will move in the direction indicated. Lengthening the lap beyond a certain limit will not add to the shear strength, Fig. 12(c). This analysis of shear stresses in a lap joint, originally shown by N. A. DeBruyne, demonstrates that the strain and therefore the stress is higher at the ends of the joint. This difference in extension of the two joined members creates a corresponding distribution of stress in the filler metal. The displacement of the forces which cause these strains, from a common axis, introduces

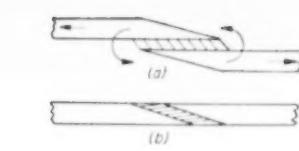


Fig. 13. Designs for Reduction of Stresses

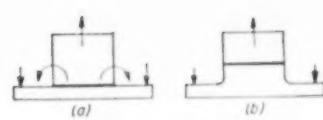


Fig. 14. Butt Joints with Superimposed Bending

a bending couple at the end of the joint which creates a tension stress in the filler metal and may start a crack.

Changes in the design of the joint members as shown in Fig. 13(a) and (b) illustrate how much of this unfavorable distribution can be overcome.

Figure 14(a) shows the application of bending forces on a butt joint that would cause additional stress and 14(b) shows how the designer can overcome this tendency.

Fatigue Strength

Much the same principles should guide the designer when fatigue strength is involved. The general rule is to design so that the brazed joint will be located in a region of low stress, as illustrated in Fig. 15, where unit stress has been

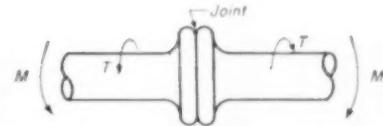


Fig. 15. Design for Reduction of Unit Stress in a Brazed Joint

decreased by increasing the section at the joint.

The available fatigue data on brazed joints are confined largely to tests on butt joints in bar stock of steel, brass and bronze, usually run in comparison with solid specimens of the same metal. The clearances that give maximum strength of joint under static loading also give maximum fatigue strength.

Figure 16 is an S-N curve for an R. R. Moore rotating-beam test of silicon

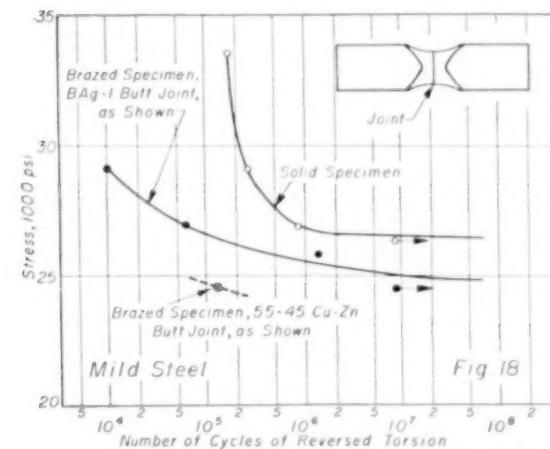
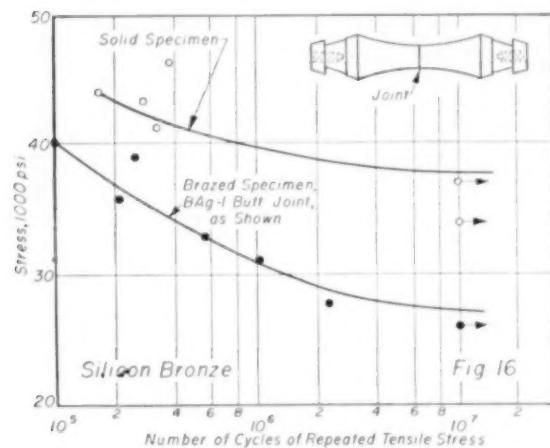


Fig. 16 to 19. Fatigue Data

Fig. 16. Fatigue limit of silver brazed silicon bronze rotating-beam specimens (Ref. 17). Fig. 17. Fatigue limit of silver brazed and unbrazed 60% Cu - 40% Zn specimens stressed in reversed torsion (Ref. 2). Fig. 18. Fatigue limit of silver brazed and unbrazed mild steel specimens stressed in reversed torsion (Ref. 2). Fig. 19. Typical fatigue curve under reversed torsional shear loading, of copper brazed joints in mild steel with a joint clearance of 0.0005 in. (Ref. 2)

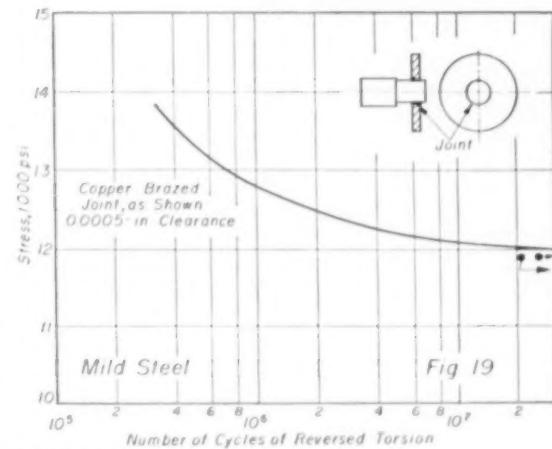


Table IV. Average Values of Joint Strength for Design Purposes
(H. R. Brooker and E. V. Beatson)

Joint Combination	Design Values for Ultimate Strength of Joints of Average Soundness, psi (based on joint area)	
	Shear	Tensile
Copper brazing alloy in mild steel (depends on fit)	22,000 to 31,000	25,000 to 49,000
High-silver quaternary brazing alloy in mild and low-alloy steel	25,000 to 45,000	38,000 to 58,000
High-silver quaternary brazing alloy in nonferrous metals	Usually exceeds that of metals joined	
Brazing brasses in mild and low-alloy steel	18,000 to 36,000	31,000 to 56,000
Brazing brasses in nonferrous metals	Comparable to that of metals joined	
Aluminum brazing alloys in aluminum	Usually exceeds that of metal joined	

bronze, butt brazed at the center with BAg-1. This specimen is about the worst design for practical application; discontinuities in the brazing layer, exposed by machining, can intersect the surface and form notches or stress raisers that will lower the fatigue limit. Also, in product design, the joint would be placed in a region of lower stress, rather than at the most highly stressed location. The silicon bronze had tensile strength of 63,000 psi and fatigue limit of 38,000 psi; the brazed joints showed a fatigue limit of 26,000 psi.

Figure 17 shows torsional fatigue behavior of brazed and unbrazed specimens of Muntz metal (60-40 Cu-Zn). The brazed joint was made with BAg-1.

**Table V. Static Shear Strength
and Fatigue Limit in Shear
for Copper Brazed Joints**
(H. R. Brooker and E. V. Beatson)

Joint Fit, in.	Shear Strength, psi	Fatigue Limit, psi
0.0005 (clearance)	25,800	10,800
0.001 (interference)	29,200	11,300
0.002 (interference)	34,000	11,800

alloy and located at the smallest part of the specimen. Both brazed and unbrazed specimens showed the same fatigue limit, 22,000 psi in torsion.

Figure 18 shows torsional fatigue limits of joints in mild steel with the same type of specimen. Brazed with an alloy of 61% Ag, 28.5% Cu and 10.5% Zn (a British standard) these specimens showed a fatigue limit of 24,500 psi, compared with 26,500 psi for the solid steel. An attempt was made to compare the silver filler metal with another containing 55% Cu and 45% Zn (BCuZn-4) but most of the specimens failed prematurely because of unsound joints. The result of one test on a sound joint is plotted in the lower part of Fig. 18.

Fatigue of copper brazed joints in mild steel is shown in Fig. 19. Table V compares torsional fatigue and shear strength of these joints for three different conditions of fit.

Impact Strength

When the filler metal is stronger than the base metal, an impact specimen with a butt joint will yield in the base metal before the joint breaks. When strong base metals are joined with a weaker filler metal, the designer should make some part of the structure weak enough to yield and absorb the impact energy before the breaking strength of the joint is exceeded.

Table VI gives results of impact tests of specimens made from bar stock $\frac{1}{4}$ in. square and then ground to 0.394 in. square after brazing, as illustrated in Fig. 20(a). With heat treated steel, the impact strength of the joint can be increased by machining the specimen as shown in 20(b); the thinner section will deform before the joint breaks. The scarf joint shown in 20(c) will also have higher impact strength because the joint intersects the surface at a distance from the center of the specimen, which is the location of maximum bending moment. As the scarf is lengthened, the joint faces approach the plane of the surface of the specimen and the stress changes from tensile to shear.

The T-joints shown at 20(d) will give considerable impact resistance when properly made with soft metals but (e) and (f) are much stronger, the strength of (f) depending on the relative thicknesses of the parts shown. With strong, hard metal (e) is the strongest and (d) should be avoided.

Table VI. Impact Tests of Unnotched Specimens of Brazed Joints
(Ref. 17, Bulletin T-4)

[See Fig. 20(a)]	Average Impact Strength, ft-lb	
Brazed With	4140 Steel	Ingot Iron
Ductile alloy	1.7	39.9
Semi-brittle alloy	1.6	12.1
Very brittle alloy	1.6	1.8

Elevated and Sub-Zero Temperatures

The strength of brazed joints at elevated temperatures is determined almost entirely by the base and filler metals used and not by the design of joint. The joint becomes weaker as the temperature increases, except where diffusion of the base metal strengthens the filler metal. Table VII gives some maximum service temperatures for which the different groups of filler metal may be used for continuous and

short-time service. The curves in Fig. 21 are from various tests; the data should not be used as design values.

High-temperature applications of brazed joints require filler metals BAgMn, BCu or BNiCr, listed in order of increasing heat resistance. The tensile and shear data reported in Fig. 22 to 25 were obtained with joints of all three filler metals in base metal S-590 heat-resisting alloy. Figure 26 is for type 347 stainless steel. All specimens were brazed with zero clearance in a dry hydrogen atmosphere. Tensile specimens were plain butt joints; shear specimens (Fig. 25) were of the tongue-and-slot double-shear type.

The tensile specimens brazed with BCu and those brazed with BAgMn consistently failed through the joint. Most of the specimens brazed with BNiCr failed through the joint, up to 1600 F; above this temperature, failures in the base metal increased with temperature.

Sub-Zero Temperature need cause no concern unless below -100 F. If low temperature is the primary design consideration, joints similar to those in the structure should be tested.

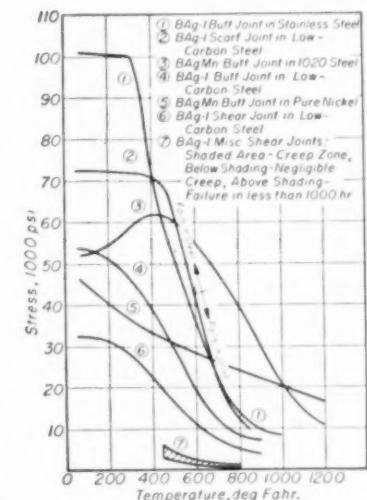


Fig. 21. Short-Time Strength Versus Temperature. Tensile strength for butt joints, shear strength for lap joints (Ref. 17)

Electrical Conductivity

A properly designed brazed joint should not add appreciable resistance to an electrical circuit. The conductivity of the filler metals is low com-

*For composition and properties of S-590 alloy, see "Heat-Resisting Alloys", pages 42 to 48 in this Supplement.

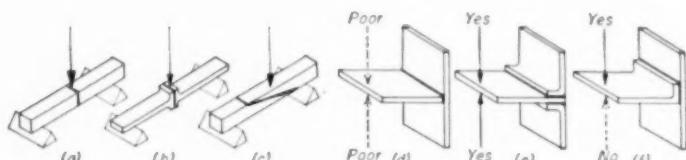


Fig. 20. Joints Loaded in Impact (Ref. 17)

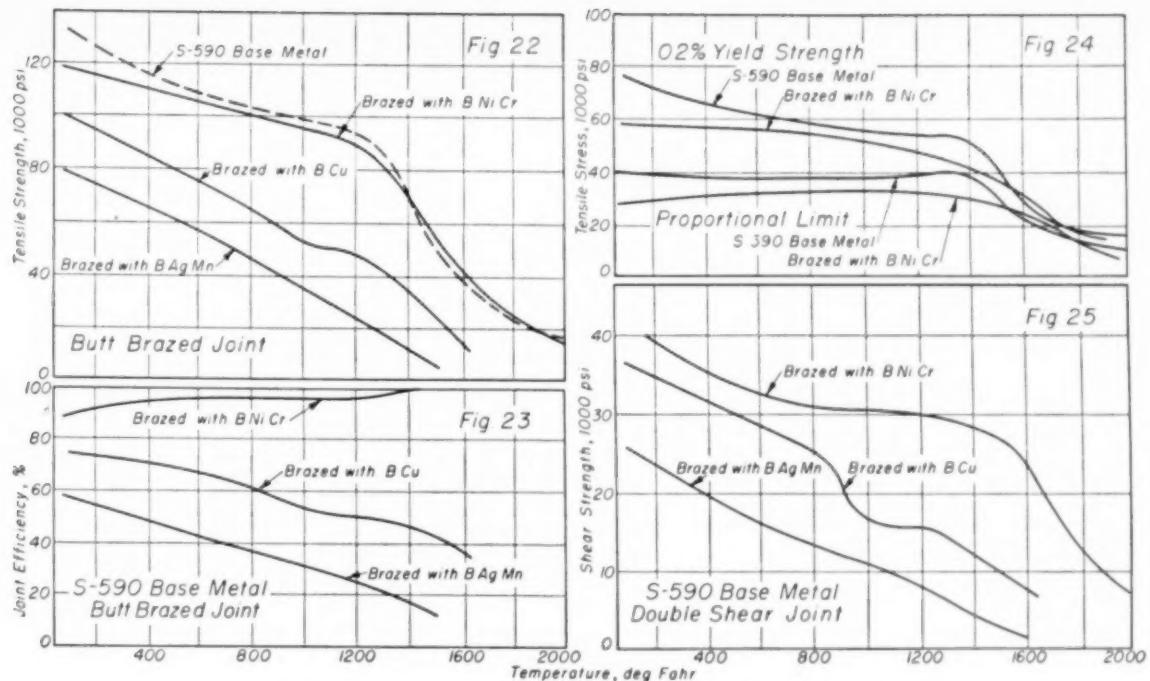


Fig. 22 to 25. Short-Time Tensile Characteristics at Elevated Temperatures

Fig. 22. Short-time tensile strength of butt joints of zero clearance on S-590 heat-resisting alloy, hydrogen brazed with three filler metals (Ref. 10). Fig. 23. Joint efficiency versus temperature; same conditions as Fig. 22 (Ref. 10). Fig. 24. Yield strength and proportional limit versus temperature; same conditions as Fig. 22 (Ref. 10). Fig. 25. Shear strength versus temperature; same conditions as Fig. 22 (Ref. 10)

pared with copper but the joint thickness is ordinarily so small compared with the length of the conductors being joined that the added resistance is negligible. In order to overcome any doubts about the effect of voids or flux inclusions, a lap joint having a length $1\frac{1}{2}$ times the thickness of the thinner member will provide a joint equivalent in conductivity to the solid member.

rious metals it is advisable to make tests of the joints.

G. H. Sistare, J. J. Halbig and L. H. Grenell have reported on the corrosion resistance of silver brazed joints in stainless steel, especially the straight-chromium grades. They give particular consideration to a form of "crevice corrosion" and point out a preference in the choice of stainless and brazing alloys, when the joints are exposed to certain corrosive conditions such as quiet tap water, especially when it contains chlorine. The copper-phosphorus filler metals should not be used for joints that will be in contact with hot gases containing sulfur in any form.

The safest course is always to make tests under the actual operating condition to which the joint will be exposed.

Brazing Processes

The brazing process governs the method of heating. Table VIII is a guide to the suitability of the several commercial brazing processes to the various base metals and filler metals.

Details of processing and recommendations on how to braze are outside the scope of this article. The following notes serve to define the salient characteristics of processes listed in Table VIII and to indicate certain features relevant to design.

Torch brazing is widely used because torches are available everywhere and because widely different masses of metal can be brazed with them. Twin-carbon arc brazing is little used because other processes accomplish the same result more effectively.

Furnace brazing is widely used for

mass production; brazing with copper filler metal (BCu) is done exclusively in furnaces, with a reducing atmosphere such as hydrogen or those obtained by cracking natural gas, ammonia, city gas, or other appropriate atmosphere.

When brazing is done in controlled atmosphere furnaces, there must be no oxides or adsorbed films; clean surfaces at the brazing temperature are a prerequisite to proper wetting of the joint faces and good bonding. Occasionally, in copper brazing in a reducing furnace atmosphere, oxides may be tolerated, providing the furnace atmosphere is

Table VII.
Maximum Service Temperatures

Filler Metal Group	Continuous Service, deg Fahr	Short-Time Service, deg Fahr
Copper-Phosphorus	300	300
Silver	300	500
Copper-Zinc	300	500
Copper	400	900
Silver-Manganese	500	900
Nickel-Chromium	1000	2000

From "The Brazing Manual", AWS (to be published 1954)

Corrosion Resistance

Little can be done in the design of the joint to influence corrosion resistance of the finished assembly. A long lap has a slight advantage over a butt joint, and a lock seam gives a greater factor of safety. Where the corrosion problem is serious, the choice of filler metal with metal being joined is the important factor. For example, the copper-base and silver-base filler metals have corrosion resistance similar to copper and copper alloys. With fer-

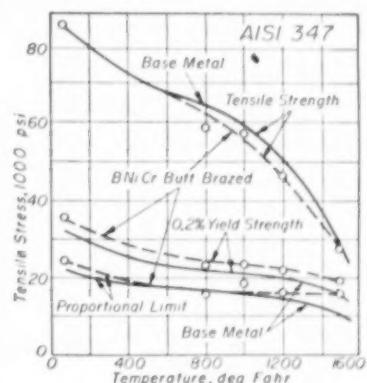


Fig. 26. Short-Time Tensile Properties of Butt Joints on Type 347 Stainless Steel, Hydrogen Braze (Ref. 10)

Table VIII. Suitable Combinations of Filler Metal, Base Metal and Brazing Process

Brazing Process	Base Metal									
	Al & Al Alloys	Mg & Mg Alloys	Ni & Ni Alloys	High-Carbon & Tool Steels	Stainless Steels	Cast Irons	Cu & Cu Alloys	Carbon & Low-Alloy Steels	Heat-Resistant Alloys	Ag, Au & Pt
Torch	BAISI	BMg	BAG BCuZn BNiCr	BAG BCuZn BNiCr	BAG BNiCr BCuZn	BAG BCuZn	BAG BCuP BCuZn	BAG BCu BCuZn BNiCr	BAG BAuMn BCuZn BNiCr	BAG BCuAu BCuP
Twin-Carbon Arc	BAISI	BMg	BAG BCuZn	BAG BCuZn	BAG	BAG BCuZn	BAG BCuP BCuZn	BAG BCuZn	.....	.....
Furnace	BAISI	BMg	BAG BAuMn BCu BNiCr	BAG BCu BCuZn BNiCr	BAG BAuMn BCu BNiCr BCuZn	BAG BCuP BCuZn	BAG BCuP BCuZn	BAG BCu BCuZn BNiCr	BAG BAuMn BCu BCuZn BNiCr	BAG BCuAu
Induction	BAISI	BMg	BAG BNiCr	BAG BCu BCuZn BNiCr	BAG BNiCr BCuZn	BAG BCuZn	BAG BCuP BCuZn	BAG BCu BCuZn	BAG BAuMn BCuZn BNiCr	BAG BCuAu
Resistance	.....	.....	BAG BCuZn	BAG	BAG	.....	BAG BCuP BCuZn	BAG BCuZn	BAG	BAG BCuAu
Dip	BAISI	BMg	BAG	BAG BCuZn	BAG	.....	BAG BCuP BCuZn	BAG BCu BCuZn	BAG	.....
Block	BAISI	BMg	BAG	BAG BCuZn	BAG	BAG BCuZn	BAG BCuP BCuZn	BAG BCuZn	.....	.....
Flow	.....	.....	.....	.....	....	BCuZn	BCuZn	BCuZn	.....	.....

From "The Brazing Manual", AWS (to be published 1954)

accessible to the oxide before or during melting of the copper, so that the oxide is reduced to a spongy form that is then readily wetted by the molten copper.

Induction brazing is widely used and, since the heat may be localized in the joint area, it is particularly useful where general heating must be avoided. Control of the rate of heating is particularly important in induction brazing. Proper location of the heating coil, rate of input and use of auxiliary coils will prevent excessive variation in the clearance between inner and outer members.

Resistance brazing is generally limited to lighter sections of metal that may be accommodated in either resistance brazing tongs or resistance welding machines modified to perform the brazing operation.

Dip brazing involves two distinct processes. In one a molten bath of brazing filler metal, usually with a covering of molten flux, is the source of heat. The parts, usually small, are dipped through the flux into the molten brazing filler metal, and this brazes the joint. The other method, known as chemical bath dip brazing, uses a bath of molten salt, wherein the parts, properly cleaned and prepared with preplaced filler metal, are immersed. Preheating may be necessary before immersion.

In block brazing, large heated metal or carbon blocks supply the heat, and the parts to be brazed are placed in close contact with the heated blocks. This process has been largely superseded by other more effective means.

Flow brazing involves the pouring of molten brazing filler metal over the joint area. The joints are usually preheated but a portion of the heat for brazing is secured from the flow of the molten filler metal over the joint.

Wetting and Bonding. Surfaces to be brazed should be free from oxides, oily

films or foreign matter. If flux is necessary, it should be spread evenly; the filler metal, as well as the base metal should be protected with flux. When shims of the filler metal are placed between the joint surfaces only a thin coating of flux is required if the surfaces have been properly cleaned and well fitted before assembling.

The design should provide flat surfaces free from uneven areas that might interfere with the capillary forces when the joint members are pressed together. Grade 100 emery will produce a good surface; highly polished surfaces or deep file cuts should be avoided. Surface roughness should be less than 100 micro-in.

Soundness of Joint. Voids are usually caused by improper cleaning or irregularities on the joint surfaces. Poor assembly or wide spacing will also prevent proper flow of the filler metal and the displacement of the flux. Uniform heating of the joint members to the brazing temperature will help.

Joints should be designed and filler metal placed so that the molten filler metal flows and displaces the flux and forces it outside the joint. When inserts are preplaced between flat members of lap joints, pressure on the joint during heating will assist in removing the flux when the filler metal becomes molten. Although sound joints are largely the result of correct brazing procedure, designs can sometimes be modified to make the brazing easier and more efficient.

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- See also references given on page 81, 1948 ASM Metals Handbook

PROCESSING AND TESTING

	Page
Carbonitriding	124
The process. Equipment. Atmospheres. Composition of case. Hardness of case. Tempering of case. Advantages of carbonitriding. Disadvantages. Cost factors.	
The Agitation of Quenching Mediums	126
Effect of flow rate of oil. Correlation curves for water, oil and molten salt.	
The Cost of Heat Treating	128
Recommended procedures for determining costs. Cost of hardening a carburized pinion gear. Comparative costs for carburizing by the batch gas method versus the continuous pack method. Comparative costs of gas and pack carburizing in two plants.	
Selection of Metal Cleaning Methods	131
Removing pigmented drawing compounds from sheet steel parts. Removing other types of soil from sheet steel parts. Removing chips and cutting fluids from machined parts. Removing polishing and buffing compounds from polished parts. Removing scale from forgings. Cleaning of small nesting parts. Cleaning sheet stock in mill processing. Health hazards.	
Press Forming of Sheet Steel	134
Short runs. Medium production. High production. Cost. Blanking. Piercing. Trimming. Shaving. Bending. Forming. Drawing. Cold extrusion. Efficient utilization of sheet.	
Machining of Steel and Cast Iron	141
Chip formation. Tool materials. Tool angles. Tool failure. Tool life. Power requirements. Cutting fluids. Minimum cost. Maximum production. Dimensions of cut. Selection of cutting speed. General recommendations for planning production.	
Machining, Joining and Finishing of Powder Metal Parts	151
Drilling. Tapping. Reaming. Turning. Boring. Milling. Shaping. Grinding. Burnishing. Coining. Joining. Impregnation and infiltration. Heat treating. Finishing.	
Steel Melting	154
Bessemer process. Basic open hearth. Basic electric furnace. Oxygen treatment. Ingots and pouring practice. Continuous casting. Vacuum and atmosphere melting.	
Selection of Methods for Nondestructive Inspection	159
Definition of methods. Evaluating soundness of steel welds. Detecting cold shuts in cast bronze bushings. Inspection of heat-resisting metals. Determining soundness of aircraft turbine disks. Sorting mixed lots of steel.	
Metallography	164
Principles of the metallurgical microscope. Phase contrast metallography. Reflecting objectives. Ultraviolet metallography. Photomicrography in color. Electrolytic polishing and etching. Cathodic vacuum etching. Electron metallography.	

Carbonitriding

By the ASM Committee on Heat Treating

CARBONITRIDING is defined as a process in which a ferrous alloy is case hardened by first being heated in a gaseous atmosphere of such composition that the alloy absorbs carbon and nitrogen simultaneously, and then being cooled at a rate that will produce desired properties. The carbon is derived from any carbon-rich gas or vaporized liquid that could be used for carburizing. Source of nitrogen is ammonia.

This process is also called dry cyaniding, gas cyaniding, ni-carburing and nitrocarburizing. Regardless of the name, the process is carried out as indicated in the definition above. Carbonitriding was little used until the late 1930's. Since 1945, its use has increased rapidly.

The purpose of carbonitriding is to impart a hard case to steel in order to provide resistance to metallic and abrasive wear. The process competes with carburizing, liquid cyaniding and, to a lesser extent, with nitriding.

Required case depth is one of the principal factors determining which process is to be used (with the exception of nitriding). For reasons mentioned below, carbonitriding is generally applied to parts that require shallow to medium depths of case, from 0.003 to 0.025 in.

Supersedes the article on page 696
of the 1948 ASM Metals Handbook

Equipment. Carbonitriding is done in a furnace chamber, retort, muffle or other closed container with an atmosphere that can supply carbon and nitrogen to the steel. Any equipment suitable for gas carburizing can generally be adapted to carbonitriding. The equipment must be able to contain an atmosphere and the atmosphere must be capable of circulating freely through the work load. Where dense loads are processed the furnace must be equipped with a fan to force the atmosphere through the work load. Where the work load is shallow or open in spacing of the parts, fan circulation of the atmosphere may not be required. For work that is to be clean and bright after quenching, the furnace must be equipped with protective-atmosphere vestibules for quenching.

Atmospheres. Many types of carbonaceous gases can be used with ammonia to make up the atmosphere for carbonitriding (Tables I and II). Raw natural gas, coke oven gases, butane and propane provide rich sources of carbon; liquid hydrocarbons which vaporize at high temperatures are also good sources. The ammonia used is the ordinary anhydrous grade available in cylinders or in bulk. When in bulk, the liquid is stored in large tanks remote from the furnace installations.

Endothermic generator gas is usually employed as a carrier gas for the ammonia and hydrocarbons. It provides movement within the furnace chamber to sweep the spent gases from the sur-

face of the work, and also to reduce the concentration of the reacting elements and thus to facilitate control of the process. This endothermic carrier gas is produced by reacting air with natural gas or other hydrocarbon gases in fixed proportions over a heated catalyst. It is typified by the following analysis: 21% CO, 40% H₂, 1% max CH₄, balance N₂ with traces of CO₂, H₂O and O₂. The composition of this carrier gas depends on the air-gas ratio before reaction. A common method of control employs measurements of the dew point or moisture content of the carrier gas as generated. Such a prepared atmosphere can be used with

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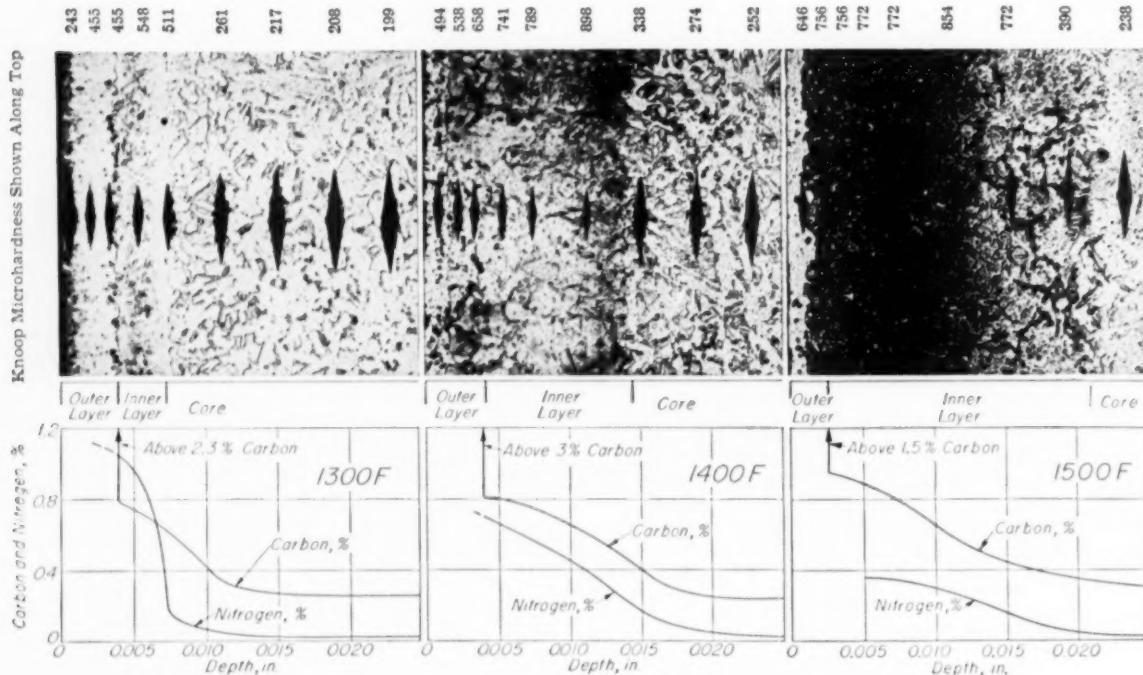


Fig. 1. Carbon, Nitrogen and Hardness Gradients and Microstructures of 1020 Steel Carbonitrided at 1300, 1400 and 1500 F for 4 Hr in an Atmosphere of 40% Ammonia, 10% Methane and 50% Carrier Gas (G. W. P. Rengstorff, M. B. Bever and C. F. Floe, Metal Progress, November 1949)

Table I. Typical Mixtures of Component Gases Used in Carbonitriding^(a)

	Constituents of Gas, % by Volume				Total Gas Flow, cu ft/hr	Furnace Volume, cu ft	Turnover per Hour
	Natural Ammonia	Gas	City Gas	Propane	Carrier Gas		
A	11	..	17	..	72	900	105
B	7	10	..	..	83	200	11
C	33	67	..	..	..	60	24
D	6	..	..	1	93	486	40
E	33 ^(b)	67	..	..	..	24	22
F	16	..	..	..	84	475	15
G	20	5	..	..	75	500	15
H	8	10	..	..	82	600	120
I	8	6	..	..	86	925	420

(a) Results of a survey of industrial carbonitriding practice by M. B. Bever, C. F. Floe and W. G. Zaruba. Last three entries added by ASM Committee on Heat Treating.

(b) Hydrocarbon introduced as fluid; atmosphere composition and turnover calculated

ammonia alone or with ammonia plus hydrocarbons to provide adequate carbon and nitrogen to produce the high case hardness desired.

In maintaining an effective carbonitriding atmosphere in the furnace or retort, contamination of the atmosphere must be avoided. Leaks in the furnace or retort, frequent door openings which cause infiltration of air, and leaks in gas or oil-fired radiant tubes which cause products of combustion to enter the furnace are detrimental.

The addition to the carbonitriding atmosphere of small percentages of rich hydrocarbons produces a slightly faster rate of carbon absorption and diffusion. Excessive hydrocarbons, however, generally produce sooting, with deleterious effects on both furnace alloy and rate of carbonitriding.

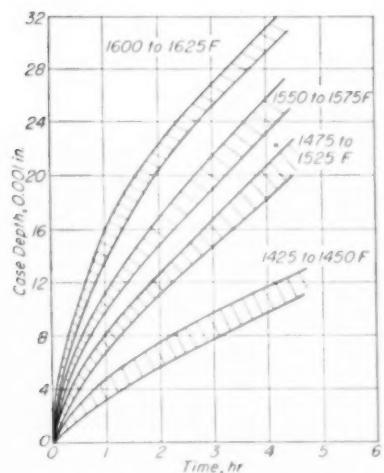


Fig. 2. Total Time-Temperature-Case Depth Relations in Carbonitriding. Results of a survey of industrial practice, by M. B. Bever, C. F. Floe and W. G. Zaruba

Different types of furnaces require different percentages of entering component gases because of the reactions of the gases with furnace brickwork and alloy. Premixing of component gases before they enter the furnace is desirable. In large, continuous carbonitriding furnaces the gases should be introduced at several points along the furnace to insure uniform distribution of ammonia and carburizing gases for reaction at the surface of the work.

Composition of the Case depends on temperature, time, atmosphere composition and type of steel. The higher the carbonitriding temperature, the less effective is the ammonia in the atmosphere. Lower temperatures favor the absorption of nitrogen. The process can be carried out at such low temperatures as to produce a "compound layer", so called because complex iron-carbon-nitrogen compounds are formed at the surface. To produce this compound layer, however, large percentages of ammonia are required. It is usually unnecessary to liquid quench parts carbonitrided in this manner, and in certain wear applications this type of case structure is suitable. However, because the diffusion rate of nitrogen and the rate of formation of the compound layer are so slow at temperatures below 1300 F, such practice is only applicable economically to shallow cases where dimensional tolerances would be difficult to maintain were the parts to be treated at high temperatures.

A carbonitrided case can contain more retained austenite than a carburized case. By careful control of the atmosphere composition, the amount of retained austenite can be minimized.

Figure 1 illustrates typical case structures obtained by carbonitriding at various temperatures and resulting case compositions. Figure 2 shows case depths for different combinations of total furnace treating time and temperature. Most carbonitriding is done between 1425 and 1625 F for parts to be quenched and between 1200 and 1450 F

for parts not requiring a liquid quench.

Hardness of Case. The hardness of the carbonitrided case will depend on its carbon and nitrogen contents, on the amount of retained austenite, and on the presence or absence of iron-carbon-nitrogen compounds as a surface layer. File hard cases are easily produced. For most carbonitrided work, hardness will exceed Rockwell C 60, or its equivalent on other scales, without difficulty. Shallow cases or austenite retention will markedly lower hardness readings.

Tempering of the Case. The presence of the nitrogen in the carbonitrided case increases its resistance to tempering compared with that prevailing in straight carburized cases; higher tempering temperatures are required to produce a given hardness. Such increased resistance to tempering may be desirable where service operating temperatures are abnormally high, or where hot straightening is advantageous. The higher tempering temperatures also decrease residual stresses.

Advantages of Carbonitriding. One major advantage of carbonitriding is that the nitrogen absorbed during processing lowers the critical cooling rate of the steel. That is, the hardenability of the case is significantly greater when nitrogen is added by carbonitriding than when the same steel is carburized only. This advantage permits the use of steels on which uniform case hardness ordinarily could not be obtained if they were carburized only and quenched. Where core properties are not important the carbonitriding process permits the use of plain low-carbon

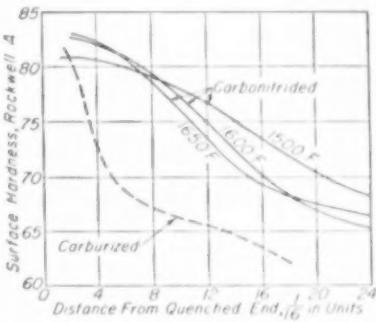


Fig. 3. End-Quench Hardenability Curves of 1020 Steel Carbonitrided at 1500, 1600 and 1650 F, Compared with the Same Steel Carburized at 1700 F. Ammonia content of the carbonitriding atmosphere was 15% at 1500 F, 10% at 1600 F and 5% at 1650 F; methane was 5%, carrier gas the remainder. (G. W. Powell, M. B. Bever and C. F. Floe, Trans. ASM, 46, 1359, 1954)

Table II. Gases Used in Carbonitriding

Gas	Function	Constituents of Gas, % by Volume								Specific Gravity
		CO ₂	O ₂	N ₂	CO	H ₂	CH ₄	C ₂ H ₆	C ₃ H ₈	
Natural Gas (Pittsburgh)	Source of Carbon	...	...	0.8	...	...	83.4	15.8	...	0.61
Natural Gas (Kansas City)	Source of Carbon	0.8	...	8.4	...	...	84.1	6.7	...	0.63
Coke Oven Gas	Source of Carbon	2.2	0.8	8.1	6.3	46.5	32.1	...	3.5	0.44
Commercial Butane	Source of Carbon	...	...	...	...	...	...	...	...	1.95
Commercial Propane	Source of Carbon	...	...	...	...	...	(C ₃ H ₈) is 93.0, and C ₂ H ₆ is 7.0)	(C ₃ H ₈) is 100.0	...	1.52
Anhydrous Ammonia	Source of Nitrogen	...	...	...	...	...	(NH ₃) is 100.0	on heating, dissociates to 75% H ₂ , 25% N ₂	0.595	...
Endothermic Generator Gas	Carrier Gas	...	...	38.0	21.0	40.0	1.0	...	...	0.60
Purified Exothermic Gas	Carrier Gas	...	...	74.0	10.0	15.0	1.0	...	...	0.83

C₂H₆ is ethane, C₃H₈ ethylene, C₆H₆ benzene, C₃H₈ propane, CH₄ methane, and C₂H₂ butane

steels, which cost less and may have better machinability.

Figure 3 illustrates the effect of carbonitriding on the case hardenability of a plain carbon steel when carbonitrided at several different temperatures, in comparison with the same steel carburized. The effect of carbonitriding in increasing hardenability is greatest at lower temperatures of carbonitriding. This increased hardenability often permits oil quenching of carbonitrided plain carbon steel parts. The benefits include minimized distortion and better control of dimensions. Straightening and final grinding operations are often eliminated.

Nitrogen also lowers the lower transformation temperature. This permits quenching from a lower temperature than possible for steels with no nitrogen, thus minimizing distortion.

Medium-carbon parts of both carbon

and alloy steel are often heated for hardening in a carbonitriding atmosphere to produce a shallow case of higher hardness and greater resistance to wear than could be provided by conventional hardening alone. Steels such as 4140, 5140, 8640 and 4340 for applications like heavy-duty gearing are treated by this method at 1550 F. In order to minimize the amount of retained austenite, the temperature may be decreased to just above the A_s temperature before quenching.

The equipment used for carbonitriding is generally of such design that it can also be used if desired for virtually all other heat treating operations. Where limited production quantities of parts are processed by more than one method, generally only one piece of equipment will be necessary.

Disadvantages of Carbonitriding. The effectiveness of ammonia is diminished

at high processing temperatures (1700 F or above) where the carburizing action is rapid. Therefore, carbonitriding is done at lower temperatures, where the time required to produce a case depth greater than about 0.025 in. is uneconomical.

In order to carbonitride selectively, parts must be protected with copper plate or proprietary stop-off paint on those areas to be kept free from case. Liquid carburizing and cyaniding permit selective case hardening merely by immersing the area of the part to be case hardened.

Cost Factors. The cost of raw materials used in carbonitriding—that is, natural or manufactured gas, carrier gas and raw ammonia—is much lower than the cost of materials used in any of the liquid case hardening methods, but greater than for gas carburizing materials.

The Agitation of Quenching Mediums

By the ASM Committee on Heat Treating

THE USUAL PURPOSE of a quenching medium is to abstract heat uniformly from steel at a rate fast enough to produce martensite. To prevent cracking and control distortion, the cooling rate should not greatly exceed the slowest rate necessary to produce martensite. The various quenching mediums available do not automatically supply all the cooling rates desired, particularly in the range of quenching speeds between those obtainable in water and still oil. The rate of cooling by oil quenching can be increased by changing the character of the oil, its temperature and viscosity, and its rate of flow past the work, or by agitation of the work in the oil.

Measurements of the rate of flow from pipes into tanks, from mechanical

stirrers and the like, have usually shown too much variation to provide quantitative information. Data obtained using specially designed equipment and reported by E. W. Weinman, R. F. Thomson and A. L. Boeghold [Trans ASM, 44, 803 (1952)] are of more general applicability. Figure 1 has been plotted from their data for scale-free bars of 9445 alloy steel heated in an exothermic atmosphere and quenched in a mineral oil at 120 F. (The oil had a Saybolt viscosity of 79 sec at 100 F.)

Figure 2, from the same source, shows the relations between bar diameter and equivalent locations on the end-quench hardenability specimen, both for scale-free bars and for those scaled by heating in air.

The smaller temperature ranges used as arbitrary criteria for $\frac{1}{4}$ -radius, $\frac{1}{2}$ -radius and the center of the bar (Table I) distort the relationship plotted in Fig. 1. However, it is quite obvious that increasing the rate of flow has the greatest influence on the cooling rate at the surface, and that the surface of a 3-in. bar can be cooled almost as fast as the surface of a 1-in. bar when the flow rate of the oil is above about 500 ft per min. It is also evident that the major advantage from agitation lies in the range between still oil and a flow rate of 200 ft per min, which, in the paper cited, is equivalent to an average hand agitation of the work piece.

Figure 3, from unpublished work of Weinman, Thomson and Boeghold, shows the relation between molten salt flow and the cooling rates of various positions in scale-free bars in a marquenching salt at 400 F. Included in the same figures are similar curves obtained from water and oil quenching, thus providing comparisons among three mediums giving a wide range of cooling rates. The data are plotted to give correlation curves for identical cooling times in quenched round bars and standard end-quench hardenability specimens. The temperature ranges for the various positions are those given in Table I. The bars were medium-carbon 9400 steels, heated in an exothermic atmosphere.

Note that small-diameter bars (and the surface of all bar sizes shown) may be cooled faster in rapidly flowing salt at 400 F than in still or mildly agitated oil at 120 F. However, as bar size increases, subsurface regions of salt-quenched bars cool slower than those quenched in still oil. This puts a limitation on section size or steel composition that will provide a fully martensitic structure by hot salt quenching.

Table I. Temperature Ranges on Which Data of Fig. 1, 2 and 3 Are Based

Quenched Bar Position	Temperature Range Criterion, deg Fahr
Surface	1350 to 600
$\frac{1}{4}$ -radius	1350 to 700
$\frac{1}{2}$ -radius	1350 to 800
Center	1350 to 900

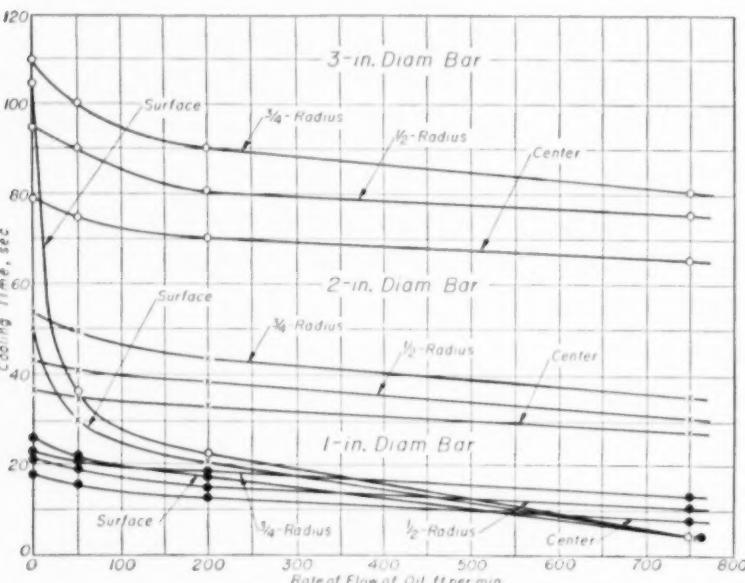


Fig. 1. Effect of Flow Rate of Quenching Oil on Cooling Time of Scale-Free Steel Bars. For temperature range criteria, see Table I, at right.

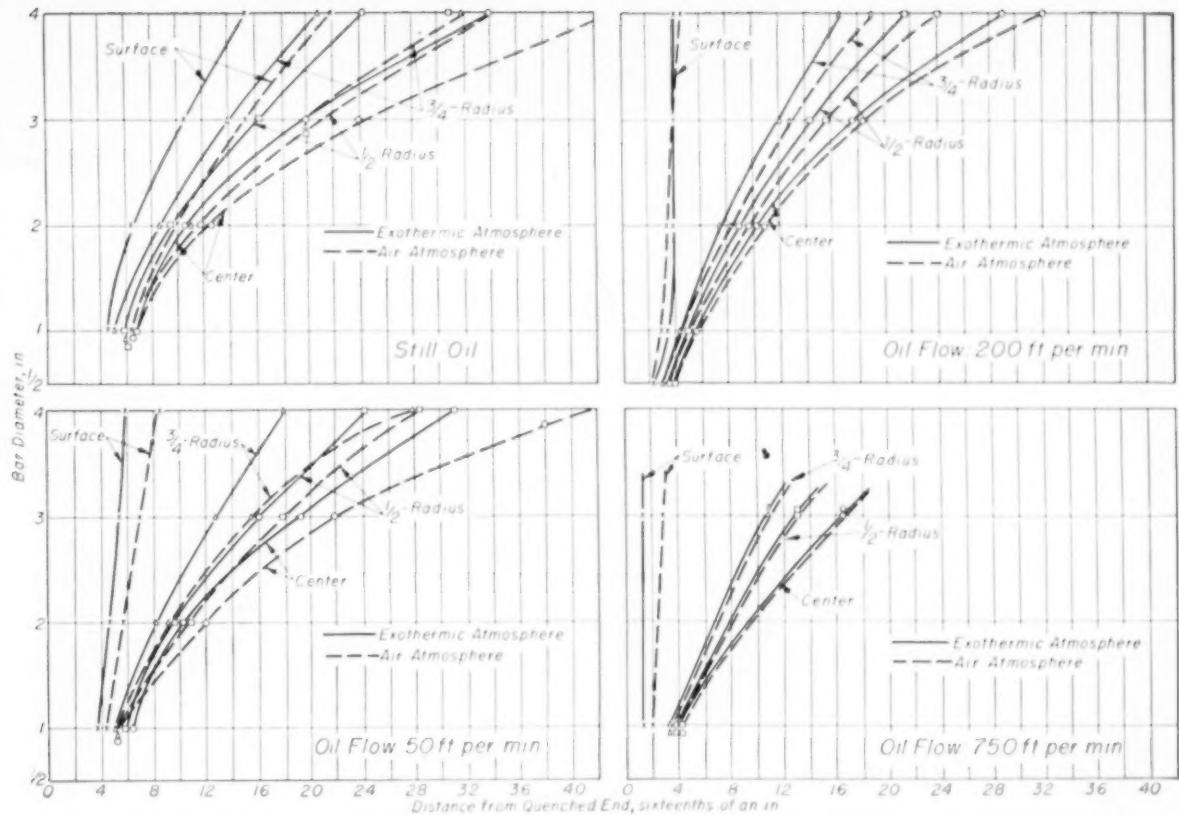


Fig. 2. Correlation Curves for Identical Cooling Times in End-Quench Hardenability Specimens and Round Bars Quenched in Oil. Temperature range criteria given in Table I. Mineral quenching oil (Saybolt viscosity of 79 sec at 100 F)

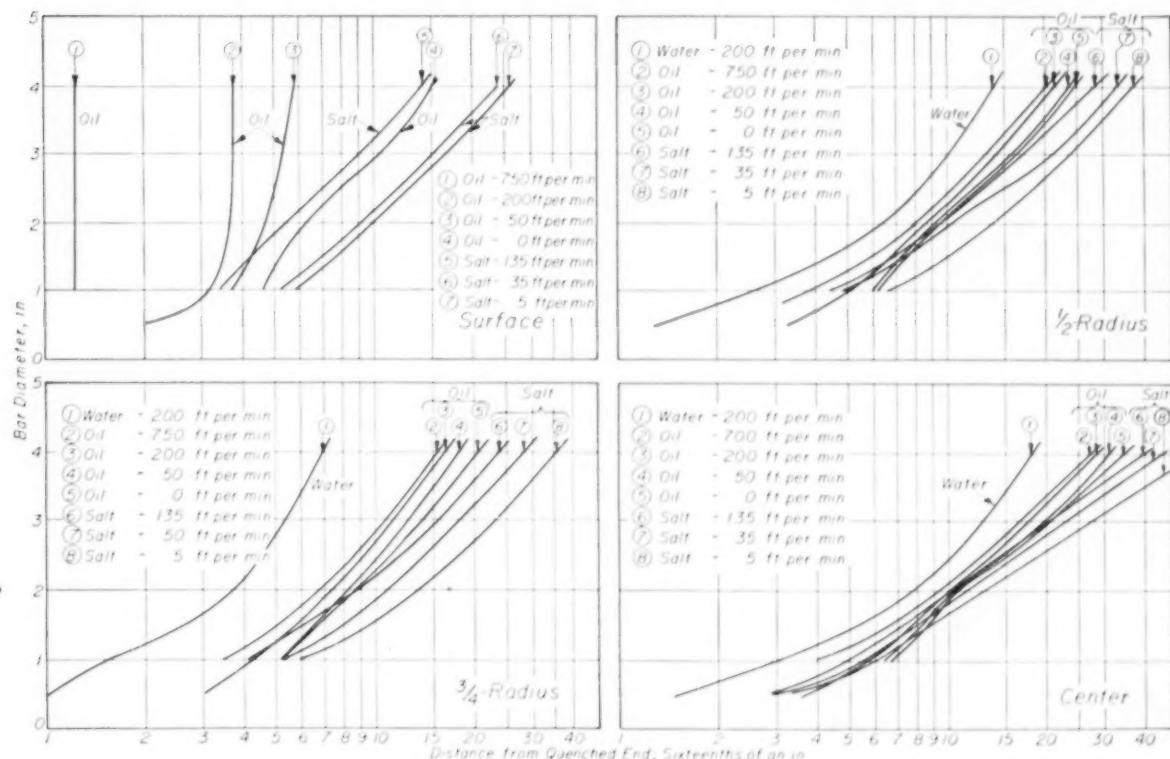


Fig. 3. Correlation Curves for Identical Cooling Times in End-Quench Hardenability Specimens and Round Bars Quenched in Hot Salt, Oil and Water. Temperature range criteria of Table I. Water at 75 F. Mineral oil (Saybolt viscosity of 79 sec at 100 F) at 120 F. Molten salt at 400 F.

The Cost of Heat Treating

By the ASM Committee on Heat Treating

BECAUSE HEAT TREATING has not been the major function of most industries, the cost of such processing has often received less attention than other metalworking operations. The increasing diversity and modernization of heat treating equipment, and the greater emphasis placed on metallurgical properties by design engineers, have made the problem more complex. One can now select any of a variety of different steels and one or more of a number of heat treatments, any combination of which might satisfy the engineering requirements of product design. With these otherwise equal alternatives, cost will in general be the factor which determines the combination actually selected.

Because of the close relation among metallurgical procedures, heat treating results and the equipment used to produce those results, cost analysis is a matter of joint concern to management, metallurgical and accounting personnel.

The investment in heat treating equipment can vary between wide extremes, with a corresponding variance in cost of operation. For small production it might occasionally be justifiable to absorb higher unit costs of operation, but a difference of a few mils per pound on high-production installations may mean hundreds of thousands of dollars per year in profit or loss.

In general, there will be some difference between any two alternatives under consideration; a fortuitous equality would be extremely improbable. Because small differences may be significant, the omission of apparently minor items may affect comparisons in a major way. Therefore it is important that the cost analysis be complete. Such cost studies may then be used:

- 1 To justify the purchase of more efficient equipment
- 2 To establish the price of the heat treated product
- 3 To reduce the cost of the product by selecting a steel and its treatment with the lowest ultimate cost
- 4 To compare the cost of an operation when routed to any of several types of furnaces
- 5 To evaluate the cost of idling furnaces which are being held at temperature
- 6 To estimate differences in the cost of a steel and its required heat treatment, as compared with that of another steel-treatment combination.

Recommended Procedures

To determine the cost of treating an individual piece, it is first necessary to calculate: (1) fixed costs, or those which pertain to the company as a whole and which persist regardless of the degree to which individual furnaces and other equipment are operated; (2) variable costs, or those related directly to the operation involved; and (3) labor costs, both direct and indirect. Once this has been done on an annual basis, for a particular furnace or other equipment, simple arithmetic will reduce the figures to an hourly basis and finally to a cost per individual piece.

The detailed schedules presented here indicate the many individual items to be included in a cost analysis of heat treating operations. After the first few calculations have established some standards, costs may be computed more easily. Two methods or formulas are recommended for determining the actual heat treating costs. In a practical sense, they are extremes, but each has a definite place in costing. Either might need modification to fit existing conditions. Both assume continuous operation. Idling of furnaces between production runs, as well as special test runs and similar contingencies, are not considered here.

Recommended ASM Form for Determining the Actual Cost of Heat Treating*

The form and method for determining actual heat treating costs can be presented best in terms of a specific example. For that purpose, the following problem is defined.

Problem 1. To determine the cost of hardening a carburized pinion gear made of 8720-H steel and weighing 76.25 lb. The furnace is of the roller-hearth type, electrically heated with three zones of 190, 100 and 37-kw rating; it is equipped for protective atmosphere operation, and a minimum of labor (one man) is required. Operation is at capacity, with no idle time. Production is 26.7 parts per hour.

Cost data for this problem are tabulated according to the recommended

*Blank forms are available from the American Society for Metals.

form in the accompanying Tables I through VI. The various items are defined as follows:

Building Expense (Table II, Item 1). Defined in detail by Table V.

Furnace or Equipment Depreciation (Table II, Item 2). Defined by Table VI. The purchased cost of the furnace includes all necessary appurtenances such as temperature control instruments and flow meters.

Property Tax and Insurance (Table II, Items 3 and 4). Equipment valuation or cost, times rates.

Interest on Investment (Table II, Item 5). The value of the building (\$180,000.00) times the floor area of the furnace (936 sq ft) divided by the total area of the building (36,250 sq ft) times the interest rate (2%). Also, the interest on furnace or equipment cost.

Overhead (Table II, Item 6). Overhead includes all costs pertaining to administration of the business, prorated against the heat treating department. These costs include the applicable amounts for nonmanufacturing departments such as engineering, metallurgical, personnel, planning, accounting, purchasing, sales, advertising and service. Of this total, the proration to the heat treating department of 62 persons is \$48,600.00, of which a portion is allocated as shown, according to the personnel actually involved in the operation being analyzed.

Energy Cost (Table III, Item 1). The rated energy consumption (327 kw, total) times the minutes per hour electrical contactors are closed (39.5 avg) divided by 60 and multiplied by the electric rate (\$0.0091) gives energy cost per hour. The energy might also be measured directly with a watt meter.

Atmosphere (Table III, Item 2). Cost

Table I. Summary of Actual Hourly Costs (Problem 1)

Fixed costs (Line 8, Table II).....	\$1,6017
Variable costs (Line 8, Table III)....	3.9547
Labor costs (Line 6, Table IV).....	3.0958
Total costs	\$8.6522
Cost per part = 26.7	\$0.3241
Cost per pound = 26.7 x 76.25	\$0.0042

Table II. Fixed Costs (Problem 1)
(Computed on an annual basis)

1 Building expense	
Floor area 936 sq ft $\times \$1.48$ (Line 13, Table V)	\$1,385.28
2 Furnace depreciation	
8.33% (rate) $\times \$59,512.49$ (Line 12, Table VI)	4,957.39
3 Property tax	
(County tax rate \times Valuation)	768.56
4 Insurance	
Rate of \$0.08 per hundred $\times \$59,512.49$ (Line 12, Table VI)	47.61
5 Interest on investment	
(a) Building value \times Interest rate	
Building floor area	
Substituting, then	
936 (sq ft)	
\$180,000.00 $\times \frac{2\%}{36,250 (\text{sq ft})}$	\$ 92.95
(b) Furnace cost (Line 12, Table VI) \times Int rate	
Substituting, then	
\$59,512.49 $\times 2\%$	1,190.25
Total interest	1,283.20
6 Overhead	
Overhead allocated to HT \times Operator for furnace	
Substituting, then	
\$48,600.00 $\times \frac{1}{62}$	783.87
7 Annual fixed costs (for furnace)	\$9,225.91
8 Fixed costs per hour	
Annual fixed costs	\$9,225.91
Productive hours per year or	5,760
	\$1,601.7

per hour to own and operate the generator (\$3.93) is multiplied by the cubic feet per hour used in the operation (2500) and divided by the cubic feet per hour of usable atmosphere generated (8000) to give atmosphere cost per hour.

Alloy Fixtures (Table III, Item 3). Heat resistant fixtures such as boxes, baskets, trays, cans, screens and the like are costed as follows: the original purchase cost (less scrap value) of all fixtures required to operate the furnace is multiplied by the treating cycle in hours and divided by the expected service life in hours to give alloy fixture cost per hour.

Supplies (Table III, Item 4). In general this includes all supplies such as quenching oils, salts or water, heating salts, bottled gas, carburizing mediums, and asbestos and fireclay for protecting holes and keyways in the work from the carburizing or quenching operation. The value of these is reduced to average hourly consumption, to which is added the related cost of heating, cooling or circulating the supplies, to give the total cost of supplies per hour.

Maintenance (Table III, Item 5). The average maintenance and repair cost (for both labor and materials)

should be evaluated for a period of one year, then divided by the annual productive hours of the particular furnace or equipment to give maintenance cost per hour.

Tooling (Table III, Item 6). Circumstances determine the need for considering this item; in the present example it is inapplicable. In general, it includes the tools required for heat treating the part in question—for instance, if a quenching die is used, the original cost of the die times its depreciation or obsolescence rate plus the applicable maintenance and repair cost would be reduced to tooling cost per hour.

Scrap and Retreatment (Table III, Item 7). Like other manufacturing operations, heat treating processes show wide ranges of experience with regard to production of work of unacceptable quality. Some machines or furnaces will produce more work of inferior quality than others. Also, cer-

Table III. Variable Costs (Problem 1)
(Computed in costs per hour)

1 Energy cost	
215 kw-hr $\times \$0.0091$	\$1,956.5
2 Atmosphere	
\$3.93 per hour \times 2500 cfb used	1,228.1
3 Alloy trays	
(24 trays per furnace charge)	
\$45.00	
5000 $\times 24 \times 1$	0.2160
4 Supplies	
Quenching oil (loss and drag-out) =	
0.57 gal per hr $\times \$0.24$ per gal	0.1368
Bottled CO ₂ gas to purge furnace when shutting down and starting up:	
96 bottles $\times \$4.08$ each	0.0680
5760 productive hr per year	
5 Maintenance	
Labor \$1,213.90 and material \$575.39	0.3106
5,760 productive hours per year	
6 Tooling	none
7 Scrap and retreatment	
Scrap \$83.68 and retreatment \$139.23	0.0387
5,760 productive hours per year	
8 Total variable costs per hour	\$3.9547

tain types of parts or certain steels are more likely than others to process unsatisfactorily. In any event, the scrap values and costs of retreatment should be evaluated or estimated, preferably on an annual basis, and reduced to scrap and retreatment cost per hour.

Direct Labor (Table IV, Item 1). The sum of all persons directly involved with operation of the furnace or other equipment, multiplied by their hourly rates, gives the base labor cost. Since production seldom equals the rated or potential output of a furnace, because of temporary interruptions and operator inefficiency, this amount should be divided by efficiency to give direct labor cost per hour.

Indirect Labor (Table IV, Item 2). The sum of all labors which contribute to the productive efforts of direct labor, such as supervision, inspection, time-keeping, receiving, trucking and shipping. There will always be arbitrary decisions as to whether certain labors should be classified as indirect labor or overhead (Table II, Item 6). The most important consideration is that they should be included one place or the other, in a consistent manner. Since indirect labor is usually constant for a given furnace or group of furnaces and sometimes for a small department, it is usually evaluated as a percentage of base labor cost.

Employee Benefits (Table IV, Item 3). The company's cost for all benefits

Table V. Building Expense
(Problems 1 and 2)
(Computed on an annual basis)

1 Depreciation (or rent)	\$ 6,000.00
2 Taxes	250.00
3 Insurance	48.00
4 Fire protection	8,108.00
5 Maintenance (bldg & grounds)	
6 Repairs (bldg & grounds)	29,223.00
7 Heat	7,468.00
8 Light	2,510.00
9 Water ... (Inc. in 5 & 6 above)	
10 Compressed air ... (Inc. in 5 & 6 above)	
11 Other items, if any	none
12 Total	\$53,607.00
Then, cost per square foot of floor area =	
\$53,607.00	
13 36,250 sq ft (bldg area)	\$1.48

Table VI. Furnace and Equipment Cost
(Problem 1)

1 Purchased cost	\$48,063.59
2 Transportation	560.00
3 Foundation and pit	830.00
4 Erection	1,075.00
5 Piping	1,103.90
6 Wiring	600.00
7 Quench and pump, installed	5,460.00
8 Motors	170.00
9 Conveyor and hoists	1,080.00
10 Painting	220.00
11 Ventilation	350.00
12 Total	\$59,512.49

Table IV. Labor Costs (Problem 1)
(Computed in costs per hour)

1 Direct labor	
1 operator at \$1.94 per hr	\$2,108.7
92% efficiency	
2 Indirect labor	
36% $\times \$1.94$ (base labor rate)	0.6984
3 Employee benefits	
Sum of all benefits	0.2402
4 Incentive pay	none
5 Premium pay	
Annual overtime, prorated	0.0485
6 Total labor costs per hour	\$3,095.8

Table VIII. Fixed Costs (Problem 2)
(Computed on an annual basis)

Item	Method			
	Pack	Cost	Extend	Gas
1 Building expense Area in sq ft $\times \$1.48$ (Line 13, Table V)	8,010		3,200	<u>$\\$4,736.00$</u>
2 Furnace depreciation $5\% \times$ installed cost (Line 13, Table XI)		\$11,654.80		
3 Property tax (County tax rate \times valuation) ..		24,675.00		<u>14,584.00</u>
4 Insurance Rate \times valuation		6,662.25		<u>3,937.68</u>
5 Interest on investment (a) $\$180,000.00 \times$ $36.250 \times 2\%$	8,010 795.48		317.79	
6 Overhead \$48,600.00 allocated to dept of 62 total personnel Personnel by method	9,870.00	10,665.48	5,833.60	<u>6,151.39</u>
7 Annual fixed costs by method		57,387.81		<u>31,210.15</u>
8 Fixed costs per hour Annual fixed costs 8400 hr per year		<u>\$6,831.9</u>		<u>\$3,715.5</u>

Table IX. Variable Costs (Problem 2)
(Computed in costs per hour)

Item	Method			
	Pack	Cost	Extend	Gas
1 Energy cost (Line 3, Table XII)		\$ 4,779.3		<u>$\\$2,763.4$</u>
2 Atmosphere \$2.32 per hour to generate 2,400 cfm for 10 furnaces which average 185 cfm		none		2,3200
3 Alloy boxes and baskets Service life in hours	7,000		5,000	3,0240
4 Supplies (a) Compound, 450 lb per furnace per day at \$115.00 per ton		6,7029		
5 Maintenance and repair Labor		3,2344		0.1804
6 Tooling		0.2325		0.7143
7 Scrap and retreatment		0.4846		2,7143
8 Total variable costs per hour		<u>\$15,433.7</u>		<u>\$11,954.5</u>

Table X. Labor Costs (Problem 2)
(Computed in costs per hour)

Item	Method			
	Pack	Cost	Extend	Gas
1 Direct labor Number of operators at \$1.94 per hour	2		1	
Number of helpers at \$1.70 per hour	2		1	
Efficiency, %	95		90	
Cost		\$ 7,663.2		<u>$\\$4,044.4$</u>
2 Indirect labor (36% of base labor)		2,6208		<u>1,3104</u>
3 Employee benefits Sum of all benefits		0.9608		<u>0.4804</u>
4 Incentive or bonus pay		none		none
5 Premium pay Saturdays, Sundays & holidays, avg		1,6252		<u>0.8126</u>
6 Total labor costs per hour		<u>\$12,8700</u>		<u>\$ 6,6478</u>

and services should be reduced to a factor of base labor cost. Items to consider are insurances for health, accident, hospitalization, workmen's compensation, unemployment and payments under the Federal Insurance Contributions Act (FICA). First aid and medical expense, safety and others are also included here.

Incentive or Bonus Pay (Table IV,

Item 4). When either of these types of payment is made, the cost should be calculated to an hourly basis.

Premium Pay (Table IV, Item 5). Overtime and holiday pay calculated to an hourly basis.

The sum of all fixed, variable and labor costs gives the total actual cost of heat treating the part, which in Problem 1 is \$0.3241 per part (Table I).

Table VII. Summary of Actual Hourly Costs (Problem 2)

Item	Method	
	Pack	Gas
Fixed costs (Line 8, Table VIII)	\$ 6,8319	<u>\$ 3,7155</u>
Variable costs (Line 8, Table IX)	15,4337	<u>11,9545</u>
Labor costs (Line 6, Table X)	12,8700	<u>6,6478</u>
Total costs	<u>\$35,1356</u>	<u>\$22,3178</u>
Number of furnaces required	3	10
Average cost per furnace	<u>\$11,7119</u>	<u>\$ 2,2318</u>
Avg lb per hr per furnace	706	206
Cost per pound	<u>\$ 0.0166</u>	<u>\$ 0.0108</u>
Savings per pound		<u>\$ 0.0058</u>

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Comparisons

When two or more competitive methods of heat treating a given part are being compared, the inclusion of all items of cost is particularly important. Again, the method and result can be presented best in terms of a specific example.

Problem 2. To determine the comparative costs for carburizing 8500 tons of steel annually by the "batch gas" method versus the "continuous pack" method in Plant A. The batch-type carburizing furnaces are gas-heated; continuous pack furnaces are of the counterflow type, electrically heated. The parts being carburized are of similar shape, differing in size and varying in weight from 1.5 to 7.5 lb each. Production time is 8400 hr per year. The specified ranges of case depth are all between 0.060 and 0.095 in.

Cost data for this problem are tabulated according to the recommended form in the accompanying Tables VII through XII. This cost analysis shows a substantial advantage for one method of carburizing in comparison with the other. These results refer to the specific set of conditions presented. It would be improper to apply them to

Table XI. Furnace and Equipment Cost (Problem 2)

Item	Method	
	Pack	Gas
1 Furnaces required	3	10
2 Purchased cost, delivered erected	\$417,000.00	\$195,400.00
3 Foundation and pit	24,800.00	
4 Installation	9,950.00	
5 Piping	10,570.00	
6 Wiring	1,700.00	
7 Crane, conveyor and hoists	30,400.00	
8 Painting	810.00	
9 Ventilation	9,050.00	
10 Bricked floor area	560.00	
11 Atmosphere generator, installed	none	8,440.00
12 Compound, storage screening and elevating	76,500.00	none
13 Total	\$493,500.00	\$291,680.00

Table XII. Energy Costs (Problem 2)
(Computed in costs per hour)

Type of Energy	Method	
	Pack	Gas
1 Electric		
Avg consumption, 179 kw-hr per furnace 179 kw-hr \times 3 furnaces \times \$0.0089 per kw-hr		\$4.7793
2 Gaseous fuel		
(a) Natural gas used 80% of year: avg consumption, 600 ccf per furnace 600 \times 10 furnaces \times 80% \times \$0.3007 per mcf	\$1,4434	
(b) Propane used 20% of year: 600 \times 10 \times 20% \times \$1.10 per mcf	1,3290	
3 Total	\$4.7793	\$2.7634

different conditions, and the example given here is not to be considered a generalized recommendation for any method of carburizing.

To emphasize the specific character of the preceding result, one further example is included, in condensed form. This problem also illustrates the differences resulting from use of the short form as compared with the example just given in detail.

Problem 3. To determine the comparative costs of batch gas and continuous pack carburizing in Plant A vs Plant B.

The costs for Plant A are those just presented, for the conditions defined in Problem 2.

In Plant B, the same two methods of carburizing are applied to an entirely different type of part, made of a different type of steel, processed under different conditions of labor and equipment. In Plant B, the data are derived from a run of 10,000 tons of parts, divided about equally between batch gas and continuous pack methods. The capacity of each continuous furnace is about five times that of each batch furnace. Production

in both is uninterrupted, 24 hr a day, 7 days a week. The specified ranges of case depth are all between 0.050 and 0.090 in.

The data are presented in Table XIII according to a Recommended Short Form (see box, above right) which excludes all fixed costs and certain items of variable cost and labor. Because the formula is brief it lends itself well to obtaining approximate costs in a short time when it is known that the excluded items of cost will not change the principal results of the comparison.

The results obtained for Plant A in a complete cost analysis (Table VII) and by the Short Form (Table XIII) show about the same relative advantage in favor of batch gas carburizing. In Plant B, the difference in cost per pound by the two carburizing methods is somewhat more than in Plant A, and the advantage lies with continuous pack carburizing. Inclusion of the items omitted in the Short Form would not alter the advantage in favor of pack carburizing in Plant B under the specified conditions, but would change the

magnitude of the difference.

Changing the conditions in either plant might change the advantage. For instance, with intermittent operations or for small lots of various case depths, the batch type of operation would be more efficient than the continuous method in Plant B. As conditions change in the direction of equalizing the costs of competitive methods, it becomes more important to make complete cost analyses; the Short Form will not disclose the true break-even point for two processes.

The principal form recommended here includes all costs and therefore can be readily adapted to special circumstances. Any successful form will appear, at first glance, to be somewhat involved and encumbered with small items. It is emphasized again that these apparently small items should not be neglected because, added together, they frequently amount to a surprisingly large part of the actual total cost, and may have a decisive effect on any comparison.

Table XIII. Comparison of Two Carburizing Methods in Two Plants (Problem 3)
(Costs per ton, shown according to the Short Form)

Item	Plant A		Plant B	
	Pack	Gas	Pack	Gas
Direct labor	\$7.24	\$3.93	\$32.10	\$22.00
Indirect labor	2.47	1.27	8.35	7.92
Expendable supplies	13.90	8.05	18.94	17.14
Maintenance				
Labor	0.22	0.69	0.16	3.65
Materials	0.46	2.64	0.85	21.52
Total estimated cost per ton	\$24.29	\$16.58	\$60.40	\$72.23
Total estimated cost per pound	0.0121	0.0083	0.0302	0.0361
Savings per pound		0.0038		0.0059

Results by Short Form shown here for Plant A may be compared with actual costs given in Tables VII to XII for the same two methods of carburizing in Plant A. In Tables VII to XII, all costs have been included in the analysis, and the total costs are 30 to 40% higher than those estimated here by the Short Form.

Classification of Prepared Atmospheres

CLASS	METHOD OF PREPARATION	AIR TO GAS RATIO (a)	ANALYSIS, BY VOLUME (a)					DEW POINT, °F.	FUEL GAS REQ'D (c)	COST (d)	NATURE OF ATMOSPHERE
			N ₂	CO (b)	CO ₂	H ₂ (b)	CH ₄				
Exothermic Base — Combustion of gas-air mixture. This may be followed by cold water, refrigeration or absorbent tower dehydration, depending on desired dew point.											
101	Exothermic base with lean mixture	9.0	86.8	1.5	10.5	1.2	—	(e)	120	0.070	Noncombustible; slightly reducing
102	Exothermic base with rich mixture	6.0	71.5	10.5	5.0	12.5	0.5	(e)	155	0.085	Combustible; toxic; medium reducing
103	Class 101 prepared directly in the furnace										
104	Class 102 prepared directly in the furnace										
105	Class 101 followed by passage through incandescent charcoal		77.8	20.1		2.1					Combustible; toxic; very reducing
106	Class 102 followed by passage through incandescent charcoal		67.3	19.3		12.9	0.5				Combustible; toxic; very reducing
112	Class 102 plus combusted mixture of chlorine, hydrocarbon fuel gas and air										
113	Class 101 with sulphur removed										
114	Class 102 with sulphur removed										
116	Class 102 carrying lithium vapor (red-line cartridge)										
118	Class 102 carrying lithium vapor (blue-line cartridge)										
Prepared Nitrogen Base — Exothermic base followed by removal of carbon dioxide and water vapor.											
201	Prepared nitrogen base with lean mixture	9.0	97.1	1.7	—	1.2	—	-40	135	0.100	Noncombustible; inert
202	Prepared nitrogen base with rich mixture	6.0	75.3	11.0		13.2	0.5	-40	160	0.120	Combustible; toxic; medium reducing
207	Class 201 plus raw hydrocarbon fuel gas										
208	Class 202 plus raw hydrocarbon fuel gas										
213	Class 201 with sulphur and odors removed										
214	Class 202 with sulphur and odors removed										
Endothermic Base — Gas-air mixture reacted in catalyst-filled externally heated chamber.											
301	Endothermic base partially reacted and quick cooled to eliminate breakdown of CO into C + CO ₂	2.6	45.1	19.6	0.4	34.6	0.3	+50	190 (f)	0.230	Combustible; toxic; very reducing
302	Endothermic base completely reacted and cooled as in Class 301	2.5	39.8	20.7	—	38.7	0.8	0 to -5	200 (f)	0.230	Combustible; toxic; very reducing
305	Class 301 followed by passage through incandescent charcoal										
307	Class 301 plus raw hydrocarbon fuel gas										
308	Class 302 plus raw hydrocarbon fuel gas										
309	Class 301 plus raw hydrocarbon fuel gas and raw ammonia										
310	Class 302 plus raw hydrocarbon fuel gas and raw ammonia										
315	Class 301 carrying lithium vapor (white-line cartridge)										
Charcoal Base — Air passed through charcoal-filled vertical retort externally heated; prepared gas drawn off at maximum temperature zone. Undesirable constituents of green charcoal eliminated by venting small portion of the gas formed at top.											
402	Charcoal base		64.1	34.7	—	1.2	—	-20	12.5 lb. charcoal	0.430	Combustible; toxic; extremely reducing
408	Class 402 plus raw hydrocarbon fuel gas										
410	Class 402 plus raw hydrocarbon fuel gas and raw ammonia										
421	Air plus ammonia and benzol passed through incandescent charcoal without external heating		63.0	33.5	1.0	2.0	0.5	-10	16.0 lb. charcoal	0.430	Combustible; toxic; extremely reducing
Ammonia Base —											
500	Ammonia, raw										
501	Ammonia dissociated in externally heated chamber	No Air	25.0	—	—	75.0	—	-60	23.5 lb. ammonia	2.00	Combustible; reducing
521	Class 501, nearly completely burned, followed by water, refrigeration or absorbent tower dehydration depending on desired dew point	1.9	99.0	—	—	1.0	—	(e)	13.7 lb. ammonia	1.20	Noncombustible; inert
522	Class 501, partially burned, followed by water, refrigeration or absorbent tower dehydration depending on desired dew point	1.3	80.0	—	—	20.0	—	(e)	14.9 lb. ammonia	1.30	Combustible; slightly reducing

(a) Analyses based on 1000-B.t.u. natural gas requiring 9.6 volumes of air for complete combustion. For other gases multiply "air to gas" ratio quoted by 0.5 for artificial gas high in hydrogen; by 0.4 for artificial gas with medium H₂; high CO; by 2.5 for propane; by 3.2 for butane.

(b) If made with artificial gas, the CO will be slightly lower and H₂ somewhat higher. With propane and butane the reverse will be true.

(c) "Fuel gas required" represents the cu.ft. of 1000-B.t.u. natural gas required to make 1000 cu.ft. of atmosphere. For other fuel gases multiply by 2.0 for high H₂O.

Metal Progress Data Sheet 78. Compiled by C. C. Elec.
Commercial Gas Section, Information Letters No. 9.

artificial gas; 2.5 for medium H₂, high CO artificial gas; 0.4 for propane; 0.3 for butane.

(d) Costs (in dollars per 1000 cu.ft. of atmosphere) are based on: Natural gas at 40¢ per 1000 cu.ft.; electricity at 1¢ per kw-hr.; water at 6¢ per 1000 gal.; charcoal at 2½¢ per lb.; ammonia at 7¢ per lb. Amortization not included.

(e) Room temperature (cooling by tap water). May be reduced to +40° F. by a refrigeration unit, or to -50° F. by absorbents.

(f) Plus 250 cu.ft. of fuel gas for heating retort per 1000 cu.ft. of prepared atmosphere.

Metal Progress Data Sheet 78. Compiled by C. C. Ecles and M. E. Shriner, from American Gas Assoc., Industrial and Commercial Gas Section Information Letter No. 9, 1949.

Commercial Gas Section, Information Letter No. 9.

Selection of Metal Cleaning Methods

By the ASM Committee on Metal Cleaning

THIS ARTICLE compares various methods of cleaning ferrous metal parts. The selection of methods is emphasized, rather than operating procedures. The 1948 Metals Handbook describes most of the processes and the effects of time, temperature, concentration, agitation and other variables.

The plan of this article is to consider specific cleaning jobs and the applicability of available methods for each. The situations discussed are: removing drawing compounds from sheet steel parts, removing scale from forgings, removing cutting fluids and chips from machined parts, removing polishing and buffering compounds, cleaning of small nestling parts, and cleaning operations involved in sheet and strip mill operations. The final section of the article deals with health hazards.

Removing Pigmented Drawing Compounds from Sheet Steel Parts

Various pigments are contained in commercial drawing compounds—for instance, lime, chalk, talc, lithopone (ZnS plus $BaSO_4$), sulfur, graphite and many others. These pigments cause cleaning difficulties because they are inert, whereas the organic portion of the compound is soluble or emulsifiable. The compounds dry and harden when left on parts for several days after the drawing operation, and the hard crust is difficult to penetrate with some common cleaners. Cleaning methods for soil of this type are compared in the following paragraphs.

Pigmented drawing compounds should be avoided on parts to be porcelain enameled.

Vapor Degreasing dissolves some of the organic material and leaves the pigmented material adhering tightly to the surface, making subsequent cleaning more difficult; also, the chemicals are costly and may be toxic. Vapor degreasing is not recommended for removing pigmented drawing compounds.

Solvent Cleaning loosens the soil so it can be removed by subsequent emulsion or alkaline cleaning. Petroleum solvent cleaners with high flash points are used for this operation; they are usually cheaper and less toxic than the chlorinated hydrocarbons. Very little equipment is necessary, principally a bucket of solvent with wiping cloths or a brush. Presoaking or solvent wiping is recommended for softening aged, hard-caked or very heavy deposits of pigmented drawing compounds.

Acid Cleaning. Phosphoric acid solutions with solvent or emulsifying components can remove pigmented drawing compounds and thin oxide films and produce a thin phosphate coating on the part. Because the chemicals and

required manual processing are expensive, acid cleaning is recommended only for large, bulky parts of low production which require subsequent painting.

Emulsion Cleaning. Both stable and multiphase emulsion cleaners will satisfactorily remove pigmented compounds immediately after the parts are drawn or after aged deposits have been loosened or wetted by previous steps. The multiphase emulsions are more

Subdivisions	Page
Removing Pigmented Drawing Compounds from Sheet Steel Parts	131
Removing Other Types of Soil from Sheet Metal Parts	131
Removing Chips and Cutting Fluids from Machined Parts	132
Removing Polishing and Buffing Compounds from Polished Parts	132
Removing Scale from Forgings	132
Cleaning Small Nestling Parts	133
Cleaning Low-Carbon Sheet and Tin-Mill Stock during Mill Operations	133
Health and Fire Hazards	134

effective than stable emulsions on drawn parts which have dried several days, and may be applied either by immersion or by spray. In tanks, multiphase cleaners separate into layers, depending on the specific gravity of their components. As the parts are lowered into the tank the layer of solvent penetrates and loosens the encrusted soil, which is removed by the water phase of the cleaner.

Emulsion cleaner chemicals cost less than vapor degreasing and solvent cleaners. Both multiphase and stable emulsion cleaners are used in spray cleaning. The difference in penetration between the two types when sprayed is less than when soaked, but the multiphase cleaner is somewhat better in either type of equipment.

Emulsion cleaners leave a microscopic film of organic material on the surface of the work which retards corrosion. Over-all cost is usually slightly higher than for alkaline cleaning.

Alkaline Cleaning is usually the most economical way to remove pigmented drawing compounds. Spray cleaning is most widely used when production is great enough to justify the equipment costs. Lower concentrations and smaller quantities of chemicals are required than for soak or electrolytic methods.

Soak-type cleaning requires violent agitation, which is still less effective than the impinging action of spray cleaning.

Electrolytic Cleaning is the most effective alkaline method and the most expensive. Precleaning is recommended

to remove gross soil before electrocleaning. The cost of racking is justified only when very clean surfaces are required. Electrolytic cleaning should be used when parts are to be electroplated later.

The effectiveness of alkaline cleaning solutions on heavy deposits may be improved by adding kerosene or an emulsion cleaner (up to 2% of the volume of the cleaning solution). If the drawing compound has hardened on the parts, presoaking or preliminary solvent softening may be required. The presoak solution should consist of about one part emulsion cleaner concentrate and four parts kerosene; the concentrate contains wetting agents, and water should not be added for maximum effectiveness. Parts are immersed manually in the presoak solution or in a solvent cleaner and placed on the alkaline cleaner conveyor line. The hard caked soil is surrounded with the emulsifying solution, and its removal by the alkaline cleaning solution is facilitated.

Removing Other Types of Soil from Sheet Metal Parts

In the forming and drawing of sheet metal parts, oils, greases and various types of unpigmented drawing compounds are used to facilitate fabrication. Often these soils must be removed prior to inspection and certain types of welding, along with any oxides or corrosion products which must always be completely removed before painting, plating or porcelain enameling.

Vapor Degreasing quickly and effectively removes unpigmented oily soil and leaves the parts clean and dry. It may also be especially suitable when space is limited for equipment, but the initial cost of vapor degreasers is high and they are costly to operate. The solvent is effective on oils and greases, but cannot remove soaps or other organic materials insoluble in the solvent. Mechanical action by spray or stream is required to remove loosened solid particles.

Emulsion Cleaners are effective in either soak or spray type of operation. They are a little more expensive, overall, than alkaline cleaners. However, they may be used at lower temperatures than alkaline cleaners and some formulations can be operated at room temperature. A film remains on the parts which protects against corrosion during storage or prior to fabrication.

Alkaline Cleaning is usually the most economical method for removing oils and unpigmented drawing compounds, whether they are mineral oils and greases, vegetable or animal oils, or fats. Solutions are generally used hot (140 to 212 F) and either saponify or emulsify the soils.

High production usually justifies the cost of multistage spray washers using low-foaming cleaners. Concentrations are much lower than for batch tanks. Spray washing is effective on parts not contaminated with heavy soils; a typical sequence is: hot cleaner, cold water rinse, hot water rinse.

For low production in batches, individual tanks and the same sequence of steps as for spray washers are recommended.

Electrolytic Alkaline Cleaning is necessary for parts that are to be plated. Straight anodic cleaning is used for

Supplements the articles on pages 299 to 306 and 725 to 730 of the 1948 ASM Metals Handbook.

most applications. For some soils a combination of cathodic and anodic cleaning is used; the sheet part is first made cathodic, then anodic. (Reversing the current removes the impurities or smut which have been deposited on the work in the cathodic cycle. For best results, separate tanks should be used.) The equipment used in this type of cleaning is expensive and the work must be racked; cost must be justified by the need for high quality work or by the unsuitability of other methods.

Acid Cleaning. Rusted parts or those oxidized in storage can be effectively cleaned by acid pickling, usually with sulfuric or muriatic acid (HCl). Sulfuric acid is generally used hot (160 to 170 F); muriatic, at room temperature. Oil and grease must be removed from the parts before acid cleaning. Electrolytic acid cleaning will remove heavy scale rapidly.

Removing Chips and Cutting Fluids from Machined Parts

Cutting and grinding fluids used in machining ferrous metals may be divided into three groups for consideration of cleaning requirements:

- 1 Plain and sulfurized mineral and fatty oils or combinations thereof, chlorinated mineral oils and sulfurized chlorinated mineral oils.
- 2 Soluble oils of either the conventional or heavy-duty type with sulfur or other additions, and soluble grinding oils with wetting agents.
- 3 "Chemical" cutting fluids which are water-soluble and generally act as cleaners. They contain soaps, amines, sodium salts of sulfated fatty alcohols, alkyl aromatic sodium salts of sulfonates or other types of water-soluble addition agents.

Usually, fluids of all three groups are easily removed and the chips fall away immediately thereafter. Plain water is often suitable; otherwise, the following methods are effective. In any method, agitation helps free the chips from the work.

Vapor Degreasing is effective on recessed areas, and is adaptable to either small job work or continuous production. It will dissolve and remove cutting fluids of the first group easily and completely. The degreaser operates at 189 F, the boiling point of trichloroethylene. Oil viscosity is low at this temperature and drying is rapid. Equipment cost is relatively high. The chlorinated solvents are also more expensive than the chemicals used in other methods. Equipment must be carefully operated to avoid excessive consumption of solvent.

Soils of the second and third groups may not be removed completely, and cause deterioration of the solvent, thus lowering efficiency. Water contamination of the solvent causes hydrolysis, producing hydrochloric acid.

Subsequent electrolytic alkaline cleaning is required if the work is to be plated.

The chlorinated solvents are non-flammable. However, they are toxic and proper ventilation is essential.

Ultrasonic Cleaning has been used in conjunction with vapor degreasing for small intricate parts. Transducers produce ultrasonic waves in degreaser fluids and focus them in an area through which the work passes. The method is expensive and is recom-

mended only when the intricate parts present a special cleaning problem.

Solvent Cleaning also preferentially removes cutting fluids of the first group. The solvents are petroleum fractions with high flash points and are a serious fire hazard. Highly concentrated fumes are injurious to workers.

Parts cleaned in a tank with a solvent are never "chemically clean" (the ultimate in commercial cleanliness, defined by the absence of any water-break). The solvent becomes contaminated with oil and as solvent evaporates, a thin layer of oil or high-boiling solvent residue is left on the work.

The process is more expensive than emulsion cleaning. Distillation equipment for reclaiming the solvent may be warranted in high production. Chlorinated solvents such as carbon tetrachloride, trichloroethylene or perchloroethylene are sometimes used, either by themselves or with petroleum fractions. They reduce the fire hazard but are toxic; special ventilation is always required.

If chemical cleanliness is needed for subsequent plating or organic finishing, an alkaline cleaning operation that removes all traces of organic matter should follow solvent cleaning.

Emulsion Cleaning removes all three types of cutting fluids and is widely used because it is relatively cheap and the fire hazard is not great. A thin organic film remains on the work and provides some protection against corrosion during processing. Emulsion cleaners are widely used as in-process cleaners, and are usually satisfactory if the work is to be painted or phosphate coated. If the work is to be plated, electrolytic alkaline cleaning must follow emulsion cleaning.

Alkaline Cleaners are effectively used in removing cutting and grinding fluids of all three types.

Removing Polishing and Buffing Compounds from Polished Parts

Polishing and buffing compounds are difficult to remove because the soil is composed of "burned-on" greases, metallic soaps and waxes contaminated with very fine particles of metal and abrasive. Selection of a buffing or polishing compound with good cleaning characteristics is desirable.

Solvent Cleaning. Cleaning with chlorinated solvents in a mechanical degreaser, or brushing or spraying with petroleum solvents, quickly removes most of the gross soil after buffing or polishing. If the parts are to be electroplated, solvent cleaning must be followed by electrolytic alkaline cleaning.

Emulsion Cleaning is satisfactory if chemical cleanliness is not required. It must always be followed by electrolytic alkaline cleaning before electroplating. Pre-soaking in undiluted emulsion cleaner or in petroleum solvent improves the action. Emulsion cleaners can also be used preliminary to other cleaning methods.

Alkaline Cleaning. The simplest method of removing soil after polishing or buffing is tank cleaning in a hot (180 F) alkaline solution containing about 6 to 8 oz per gal of water. Cleaning action of some solutions of this type can be improved by adding soap or some other surface active agent. These solutions are not very fast, and the wet

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parts must usually be brushed with a tampico brush after soaking to remove the last traces of buffing compound. Water rinses should follow cleaning; a spray is usually superior to immersion.

Alkaline solutions without soap additives are used in power spray washers, which may be satisfactory where chemical cleanliness is not required. Solutions contain a maximum of 1 oz of dry alkali per gal of cleaner; temperature is 160 F or over. Most washers have two or more stages for rinsing and drying.

Electrolytic Alkaline Cleaning gives the best results, and is required for nearly all parts to be electroplated, either as the sole method or, more desirable, following preliminary cleaning by one of the others. Cathodic cleaning can be used; however, because some metallic and even some nonmetallic particles are deposited on the parts, a reversal to anodic cleaning as a final step is recommended. The piece can, of course, be made the anode for the entire time.

Electrolytic cleaner concentrations range from 3 to 10 oz per gal; temperature range is 160 to 200 F. Spray rinsing or agitation is required. Even with electrolytic cleaning, inert soil particles must often be brushed out of small crevices.

Acid Cleaning. A short dip in dilute sulfuric acid, muriatic acid (HCl) or other acid solution is sometimes added to the cleaning sequence to remove any tarnish or fine particles which remain after alkaline or other cleaning, and is generally used after electrolytic cleaning. If parts are to go to an alkaline plating solution after the acid dip, they should be rinsed in water and then dipped in a neutralizing sodium cyanide or other compatible alkaline solution before passing to the plating solution.

Removing Scale from Forgings

Acid Pickling is the most common method of descaling forgings. Parts should be free from organic matter and alkaline compounds prior to pickling.

For most carbon or low-alloy steels, a 5 to 25% sulfuric acid solution at 140 to 180 F will descale effectively. Acid concentration of 8 to 10% is generally

preferred; increasing the acid content beyond 25% does not increase the speed of cleaning.

Muriatic acid (HCl) may be used alone or in combination with sulfuric acid when the higher cost of the acid is justified by shorter cycles. A 10% sulfuric, 2 to 10% (by volume) muriatic mixture at 150 to 170 F is effective on stainless steel forgings. Straight muriatic solutions from 15 to 50% by volume are sometimes used.

Pitting can be minimized by inhibitors, which also increase bath life by decreasing the amount of metal dissolved. Foaming agents decrease the tendency of the bath to throw a fine spray.

Forgings must be thoroughly rinsed immediately after pickling. A spray rinse is recommended, followed by a neutralizing dip in a weak alkaline solution.

Electrolytic Pickling will remove forging and heat treating scale much more rapidly than conventional still acid pickling, particularly from stainless steel.

Salt Bath Descaling is faster than acid pickling, gives less pitting, better surface finish, no loss of metal, and simplification of solution disposal. The chief disadvantage is higher cost. Molten salts are especially useful for cleaning stainless steels and other highly alloyed ferrous materials. Methods are discussed on page 290 of the 1948 Handbook.

Mechanical Scale Removal. Tumbling is the cheapest method of scale removal and works well when forging impressions are not too deep. Adding sawdust to the tumbling charge sometimes improves the finish. Wooden blocks should be packed between large forgings to prevent distortion. For small forgings, satisfactory results are obtained by wet tumbling with aluminum oxide or "stone" chips, silica, or other abrasive. Dilute acid solutions are often used in the charge to accelerate removal of scale. After tumbling, parts are thoroughly rinsed in water and dried.

Blast cleaning is used extensively to remove forging scale. Heavy scale is cut and loosened rapidly with metallic shot or grit. The centrifugal type of equipment—barrel, table, or special cabinet—is generally preferred to the compressed air method. However, air-blast units are useful for large parts or for surfaces inaccessible with other methods. Forgings may be pickled first to loosen the scale.

Blast cleaning is a little more expensive than tumbling, and is best suited for parts with deep, narrow crevices. Conversely, this method may introduce machining difficulties because of embedded shot, grit or oxides. If this occurs, one of the other cleaning methods discussed here should be used.

Choice of shot depends on the type of finish desired and the operating conditions. If work is free from grease and shot recovery is high, cut shot should be considered despite the high initial cost. Cast iron shot is cheap but breaks down rapidly in service. Steel or malleable iron shot is intermediate in cost and will outlast cast iron. Size of shot is determined by the surface finish requirements.

Wet blasting, in which the parts are subjected to a stream of water-suspended abrasive, produces a fine surface finish and is sometimes used for removing light scale.

Brushing is the least used method of descaling, but is satisfactory for removing light puffy scale. It is better suited for parts made of formed tubing than for closed die forgings. Heavy wire brushes, knot-type, are used for forgings. Scale should first be broken by hammer peening or other mechanical means.

Cleaning of Small Nestling Parts

In cleaning small nestling objects such as gun parts, rivets, bolts, nuts, and washers, the problem is to get the cleaning solution to all surfaces in sufficient amount to clean effectively, and then to rinse the cleaner away. The preferred method is to rotate or tumble the parts during immersion or spray cleaning and rinsing.

Ordinarily both cleaning and rinsing are done in the same machine, and frequently there is an added stage for forced drying. Helix-type conveyors fitted with baffles can be used to tumble the parts. Scoop-type automatic cleaning machines combine immersion in the cleaning solutions and rinses with a tumbling action. Emulsion and alkaline cleaners are both suitable; the choice is dictated by cost and subsequent processing. Alkalies are usually cheaper and produce cleaner parts; emulsion cleaners generally leave a protective coating on the parts.

Parts can be deburred and cleaned in a simple tumbling barrel. Liquid cleaning solutions may be used in the barrel, or dry materials such as sawdust or cob meal, with or without an added abrasive, may be similarly utilized.

In solvent cleaning of small parts, the solvent is usually redistilled two or more times during the cleaning cycle. When petroleum solvents are used, a closed container fitted with a reflux condenser (vented to outside atmosphere to eliminate fire hazards) provides a satisfactory means of reducing the loss of solvent. Equipment is also available in which parts contained in a basket are agitated in a cold solvent bath by use of a compressed air motor. These machines are equipped with a fusible-link type of fire-protecting cover which makes them suitable for most factory installations.

Chlorinated solvents are used in equipment wherein baskets of parts are hung in condensing solvent vapors.

Cleaning Low-Carbon Sheet and Tin-Mill Stock during Mill Operations

Cleaning of low-carbon sheet, strip and tin-mill stock is determined by the quality required in the finished product or by subsequent mill operations, especially metallic and nonmetallic coating.

Continuous Pickling is used to remove oxides formed during hot rolling, from finished heavy-gage sheet and strip and from steel for subsequent cold reduction to sheet and tin-mill products. Acid concentration and temperature are usually higher than in batch pickling—6 to 26% by volume of 100% sulfuric acid at about 200 F. Scale should be broken mechanically by flexing or otherwise prior to pickling.

Batch Pickling is used for vitreous enameling sheets, some hot rolled sheets for hot dipped tin plate, certain types of galvanized and long terne coatings,

short terne coatings, and low-alloy high-strength steels. Sulfuric acid is generally used in concentrations from 2 to 12% at 150 to 190 F. Cold reduced, alkaline cleaned, box annealed and temper rolled steels for hot dipped tin plate require the least amount of time in acid pickling because the annealing oxide is usually light and easy to remove. (Long times must be avoided with these products to prevent hydrogen embrittlement; the danger is less for hot rolled steel.) Bessemer steels are noted for their fast pickling action. Hot rolled sheets and those for vitreous enameling require longer pickling times to remove heavy oxide formed at normalizing temperatures; 10 to 20 min at 175 to 190 F with sulfuric acid concentration of 10 to 12% is usual.

Batch pickling is followed by dip rinsing. If a "white" sheet is desired—that is, one particularly free from objectionable carbon, iron salt or "smut"—a weak solution of muriatic acid (HCl) is beneficial, often in conjunction with scrubbing and drying lines where the pickled sheets are first immersed in the acid, scrubbed with roll brushes, rinsed and dried. When this white pickling product is intended for hot dipped tin plate it is stored in a bosh or steel tank containing 0.1% muriatic acid solution until ready for tinning.

Electrolytic Pickling, prior to continuous metallic coating operations, either electrolytic or hot dip, is much more rapid than still pickling and is particularly well adapted to high-speed continuous lines because of the greater evolution of hydrogen during the process. This evolution of gas agitates the pickling solution, chemically reduces oxides of iron, and loosens contaminants from the surface of the steel.

Electrolytic pickling is used on a large scale in continuous electrolytic tin plating lines. The steel has usually been processed by cold reduction, alkaline cleaning, annealing in protective atmospheres and temper rolling. The surface, although bright, often contains small amounts of oxides, carbon and other residues from previous operations. Acid is generally cold sulfuric, in concentrations up to 35%. Muriatic acid is sometimes used.

Various strip polarities are employed ranging from single polarity (anodic or cathodic) to combinations or reversals of polarity. The steel is made the anode if some metal must be dissolved and the cathode if hydrogen evolution is necessary for agitation.

Electrolytic pickling operations are followed by dip rinsing and sometimes by roll brushing or scrubbing, which further cleans the surface prior to the plating process.

Alkaline Cleaning. Cold reduced steels are often alkaline cleaned prior to annealing. Product so treated includes tin mill black plate, steel to be hot dipped and electrolytically tinned, steel to be hot dip terne coated and some cold rolled sheet steels.

Oils or lubricants used in cold rolling may be animal or vegetable fats with varying amounts of free fatty acids, mineral oils, or mixtures of mineral oils and fats. Since the cold rolling process may raise the temperature of the strip to 400 F, polymerization products are present, along with metallic soaps, oils from mill bearings, and finely divided iron compounds. If the coil is allowed to cool and the oil congeals, cleaning is

more difficult. The most commonly used chemicals are mixtures of caustic soda, sodium carbonate, silicates or phosphates, with or without surface active agents.

Electrolytic Alkaline Cleaning has merit for removing the more complex soils at high speeds. Either cathodic-anodic or anodic-cathodic cleaning is used, with some preference for having the anodic pass last in order to unplate any films or smut. Current densities range from 30 to 80 amp per sq ft.

Most units also scrub off any residual soil with roll brushes after the alkaline cleaning and prior to rinsing or as an intermediate stage in the alkaline cleaning tank. Maintenance of brushes is extremely important to avoid streaking. Rinsing with copious amounts of hot water is preferred for removing salt drag-out and to aid in drying the strip.

Some electrolytic tinning lines also employ alkaline cleaning before electrolytic pickling. The function of these cleaning operations is to remove oils picked up in temper rolling and also to prepare the strip for electrolytic pickling. Anodic polarity is preferred.

Abrasives Cleaning. Mechanical blasting is particularly well suited for heavy gage sheets for galvanizing. The principal advantage is that heavy zinc coatings adhere better to such a surface.

Health and Fire Hazards

Some metal cleaning chemicals are injurious to health and some are a fire hazard.

Acids. Sulfuric, muriatic and phosphoric acids are dangerous to the skin. Sulfuric is a powerful dehydrating agent, which accounts for much of the "burning" and destructive action of this acid.

Muriatic acid gives off HCl gas which is immediately irritating when inhaled in concentrations of 5 ppm (parts per million) or more. Lower concentrations are apparently less harmful, but they may promote tooth decay.

Sulfuric and phosphoric acids are found in the air only when dispersed as a mist. According to H. B. Elkins,¹ concentrations of sulfuric acid much in excess of 1 ppm may be intensely irritating to the upper respiratory passage. Damage to the teeth has also been reported from the fumes of this acid.

The irritation from contact with these acids and acid fumes is usually sufficient warning to cause persons exposed to withdraw to a safe distance.

Alkalies. Alkaline cleaners usually contain alkalies which are intensely irritating to the upper respiratory organs when dispersed as dust or mist. They are also strong skin irritants and especially damaging to the eyes. Data on permissible concentrations are not available but subjective evaluation usually should provide a sufficient warning.

Solvents. Paraffin hydrocarbons with boiling points from 104 to 212 F predominate in anesthetic action. As the volatility decreases the irritating action becomes more pronounced. Kerosene is not volatile enough to be an anesthesia hazard under most conditions but is primarily an irritant. It is generally accepted that if concentrations are too low to cause dizziness, excitement, or other symptoms of narcosis, the probability of cumulative effect is slight.

The fire hazard of volatile petroleum

hydrocarbons is greater than the health hazard. However, gasoline vapor and air will not explode until the concentration exceeds 20,000 ppm (2%) but symptoms of narcosis may occur with 1000 ppm (0.1%) concentration.

Carbon tetrachloride is one of the most harmful of the common solvents. Continued exposure to concentrations of 50 to 100 ppm will produce chronic effects such as nausea, loss of appetite and vomiting. Higher concentrations will cause jaundice. Severe and even fatal liver damage has occurred with exposure to concentrations between 100 and 200 ppm. The fatal cases have generally occurred when using it in fire fighting or from injudicious use of this solvent in a confined space. Maximum allowable concentration, according to K. B. Lehman and F. Flury² is 30 ppm. H. B. Elkins¹ states: "Alcoholism predisposes to carbon tetrachloride poisoning, and heavy drinkers should not be allowed to work with this solvent."

Trichloroethylene has relatively slight toxic effect as compared with carbon tetrachloride. However, maintenance men have lost their lives climbing inside tanks containing very high concentrations of trichloroethylene vapors. Death was attributed to the strong narcotic power. Lehman and Flury recommend a maximum allowable concentration of 190 ppm for trichloroethylene.

Tetrachloroethylene, sometimes called perchloroethylene, is a strong narcotic with little other toxic effect. It is recommended when a nonflammable solvent of low volatility is desired.

References

1 Harvey B. Elkins, "The Chemistry of Industrial Toxicology", John Wiley and Sons, Inc., New York (1950)

2 K. B. Lehman and F. Flury, "Toxicology and Hygiene of Industrial Solvents", translated by King and Smith, Williams and Wilkins Co. (1943)

Press Forming of Sheet Steel

By the ASM Committee on Forming

THIS ARTICLE deals with the cold forming of sheet steel in hydraulic or mechanical presses. The general term "forming" here includes blanking, punching, bending, drawing and numerous other similar or more specialized processes.

The point of view of this article is mechanical rather than metallurgical. Factors influencing productivity are emphasized, rather than those governing the design of stamped parts. The design and construction of presses are also excluded. Selection of tool materials for all of the operations discussed is dealt with on pages 21 to 33.

The advantages and limitations of various methods of tooling are considered, without detailed consideration of tool design. The analysis here is intended primarily as an aid in selecting a method and determining the number of operations required for most economical production.

The quantity of parts required is of major importance in determining the method of manufacture. Therefore, the discussion begins with a brief description of short-run, medium- and high-production methods.

Short-Run Methods

Short-run methods range from conventional tin-shop manufacturing of a few parts at high unit labor cost, to press methods for quantities up to about 10,000 at low tooling cost and medium labor cost.

Short-Run Tooling for Press Operations. The basic principle of short-run tooling is to make the part in separate,

Subdivision	Page
Short-Run Methods	134
Medium Production	135
High Production	135
Cost of Parts	135
Blanking	136
Piercing	136
Trimming	137
Shaving	137
Bending and Forming	137
Deep Drawing	138
Cold Extrusion	139
Utilization of Metal	140

successive operations set up to minimize tool costs. The blank is die-cut to insure duplication and close registration and to permit close tolerances on subsequent manually fed operations. Piercing, notching and forming of standard shapes are economical with stock dies; special form contours and drawing operations add toolmaking costs which are less than in other types of tooling for equivalent contours.

Short-run tools are simplified by using thinner dies and simpler operations, and by substituting hand operations for machine operations in the construction. From the standpoint of economy in tooling cost, die sets are often omitted, and then only the die and punch are required, installed directly into a fixture permanently fitted to each press. Most of the tooling is thus standardized for repeated use on job after job. Often one press is used exclusively for blanking and another for piercing, thus saving set-up time on consecutive jobs. Tolerances of ± 0.002 in. or less can be held.

This subject is not included in the 1948 ASM Metals Handbook.

Very Short-Run Methods. Standard equipment (not involving presses) such as squaring shears, notching equipment, bending brakes, and nibblers are used for individual parts of simple design—for example, furnace shells, air-conditioning ducts and rain gutters. This method is limited to simple blanks with tolerances of $\pm 1/32$ in. or more. Diameters of fractional-inch holes pierced in standard hole-piercing machines can be held to within ± 0.005 in. but location will vary $\pm 1/32$ in. or more. Tolerances on bend locations will be $\pm 1/32$ in. added to the tolerance on the blank outline. Cup-shaped parts less than 18-in. in diam can be spun and lathe-trimmed to normal tolerances of $\pm 1/32$ in. or to expensive tolerances of ± 0.005 in. per in. diam.

Ordinary machine tools, in conjunction with conventional sheet metal equipment, are often used to produce small quantities of parts at many times the cost of the last method discussed. Tolerances of ± 0.003 in. would be normal shop practice, except on location of bends in V-dies or on hand-filed outlines, where tolerances average ± 0.004 in. Location of holes in hand work is usually ± 0.005 in. or more, but some skilled workers can consistently hold ± 0.003 in. in simple layouts. Tolerances on angles of bend involve springback and depend on the temper and thickness of the sheet, as well as any error of the V-die or bending brake.

Medium Production

This is the tooling used in most production plants and may be regarded as the conventional method. It is most economical for quantities between 10,000 and 100,000 pieces. Tools are mounted in die sets to avoid damage during set-up and to reduce the frequency of sharpening and repair. The processing department should be sure the part design is final because tooling costs are high.

Single-Operation Tools are used where the size and shape of part prevents group operations—for example, some large automotive parts. Long die life and accuracy are emphasized in the construction of tools. "Cushions" are often necessary to provide pressure for drawing or stripping. Work transfer attachments are sometimes incorporated to move parts from one machine to another.

Multiple-Operation Tools are used when the design of part will permit two or more operations in one tool and one stroke of the press—for example, blanking, drawing and piercing a cup or piercing, cutting off and forming the part shown in Fig. 1. Quantities of 10,000 to 100,000 pieces usually justify this tooling; it might be used for less than 10,000 pieces to obtain high accuracy of location of holes relative to each other and of holes relative to the die-cut edges. When bends are included in these one-stroke operations, tolerances may vary more than in a two-station tool because of the less accurate registration of the blank. The cost of high production is reduced considerably with this type of tooling.

Tonnage, size, stroke, shut height, opening through bed or back, and speed of the press can affect the proper operation of a tool. Rate of production usually depends on the

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nage which the press must be able to deliver equals the total of the maximum tonnages of the individual operations, regardless of the point where the forces act.

The stroke of the press must be at least two times the depth of the part, plus ejection clearances, plus the stroke movement during the time required to feed the stock. Automatic high-speed presses are either straight-side with openings in each side of the housing or the four-post movable-platen type. Coils are preferred over strip; the latter requires hand feeding and must be sheared to an exact length not less than the distance between feed rolls. Fairly heavy (thick) coiled material requires a stock straightener on the press.

Transfer Presses have a series of punches in line on individual vertical rams spaced according to the size of press. Die sections for the different operations are mounted below the punches. The individual rams of the press are actuated simultaneously by one master crankshaft or independently by cams. The first operation is to punch out a blank from the coil, which is usually fed in at a right angle to the direction of transfer movement. Mechanically operated fingers grasp the blank by its edges and slide it to the second operation. A second set of fingers slides the part from the second to the third station, and so on. Sometimes, in the last operation, movable tools at right angles to the ram perform additional operations not feasible on automatic presses. If the part cannot be completed in these operations, subsequent work may be done on another single-ram or dial-feed press.

Dial Feeds are generally used for secondary or supplementary operations that cannot be performed on the parent tooling. The dial-feed attachment, 12 in. to 8 ft diam, is mounted on the bolster plate of an inclinable press in its vertical position or on a straight-side press. Die cavities machined to the shape of the workpiece are mounted in stations near the edge of the dial and indexed by a mechanism on the press to position the work under one or more punches. The dial is locked in place during each operation to

speed of equipment and the facilities for feeding stock and removing parts. Roll feeds and scrap cutters are sometimes utilized, so the maximum speed of the press can be attained.

High Production

When more than about 50,000 parts are to be made, three different methods are available employing high-speed automatic or semi-automatic equipment: (1) presses with automatic feeds and progressive dies, (2) transfer presses and tooling, and (3) dial-feed presses and tooling.

Progressive Dies have multiple tooling stations which consecutively blank, pierce, bend or shallow draw until the

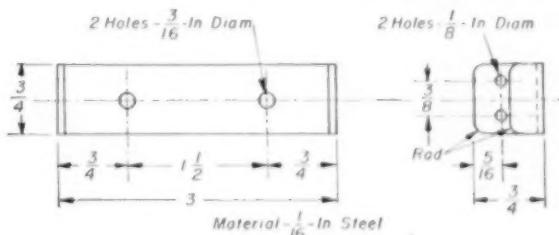


Fig. 1. Example Part

finished part is cut out of the carrier strip. These tools involve the lowest labor costs for running the parts. Coiled strip is normally fed automatically to pilot pins which, at each station, locate in pilot holes pierced out of the stock in the first operation. Forming and drawing operations are limited with progressive dies, which may cost twice as much as single-operation tools.

Conservatively figured, the total ton-

assure alignment of punch and die. Medium-sized parts can be fed by hand; small parts can be fed automatically from hoppers.

Cost of Parts

The more costly tools, which make parts in a single press stroke, minimize labor cost per part. If the quantity of parts is sufficient to save the difference, the more costly tools should be chosen.

Direct labor costs for running the parts are least in progressive and transfer-type tooling. Labor costs in dial-feed equipment depend on the feeding method and are usually added to previous operations on other tools.

Tooling cost of progressive dies for presses with automatic feeds may be twice as much as for conventional dies to do the same operations. Tooling for transfer presses is less costly than for automatic presses but more than for dial-feed presses. Progressive dies are built as an integral unit. In transfer

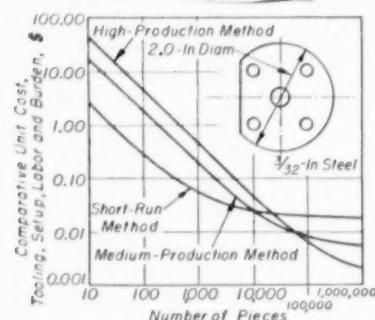


Fig. 2. Comparative Unit Cost of a Stamped Part with Quantity for Three Methods of Tooling. Note logarithmic scales.

presses, preparation time is greater because each operation is set up individually.

Figure 2 shows the cost to produce different quantities of the part shown by three methods of tooling—short-run, medium- and high-production. The cost of tooling, set up, labor and burden are included. The graph shows that the short-run method gives the lowest cost per piece for quantities up to 10,000; medium-production methods are the most economical from 10,000 to 50,000 pieces, and the high-production method shows considerable savings when more than 100,000 pieces are required.

The break-even point on various parts will be from 3000 to 30,000 for short-run versus conventional tooling. Break points between medium- and high-production tooling may have even wider variations.

Blanking

Blanking is cutting a desired shape from a sheet of metal. The simplest blanking die is the "blank through" die; the stock is fed across the female die and the punch pushes the blank through the die and bolster into a receptacle under the press. It makes plain blanks without holes cheaply.

One of several strippers may be used to strip the scrap off the punch. The cheapest are the solid strippers and hook strippers, which act as both back and end gages. A spring-actuated stripper fastened to the upper die by shoulder screws is probably the best because it does not interfere with the operator's view of his gages and material.

Another commonly used blanking die is the compound "blank and pierce" die which is the reverse of the "blank through" die; the female die is in the upper assembly and the punch is on the bottom (Fig. 3). The punch for

the blank also acts as the die for the pierced holes. The advantages of this combination are that the work can be held as flat as is usually required for a commercial stamping, and holes may be pierced at the same time, in close location with the outside. The slugs are pushed through the bed of the press and the blank stays in the female die until blown through the back of the press by a timed air blast.

The shear is ground on the female die and the piercing punches, or the punches may be staggered in length to produce the same results. Stock must be fed so as to avoid half blanks in a compound die which would set up a side thrust and either break or shear the punch or the die or both.

High-production piercing and blanking are done in separate stations. The operation is faster than in a compound die because a shorter stroke may be used and the slugs and blank are pushed through the dies. Inaccurate piloting and errors in feeding the stock necessitate looser part tolerances than in a compound blank-and-pierce die.

This type of die can be used only in straight-line blanking, and stock cannot be reversed to conserve metal as in a compound die. For an irregular blank, a two-impression die is used to produce two blanks simultaneously and conserve stock.

To eliminate the blanking operation entirely, and to minimize scrap, a "pierce and cut-off" die of very low cost can be used where no close tolerance is required on the length of part. This is a two-station die which pierces holes and other shapes in the first station and cuts off the part in the second station. Holes can be located as accurately as in any other tooling but edge

bending combined with cutting off (Fig. 4). To produce close-tolerance work on this type of tooling, a spring stripper, rather than a solid stripper, must be used to hold the stock securely so that impact of the cut-off punch will not snap the strip away from the cut edge before the piercing punches have begun to cut.

Proper clearance makes for a clean blank. Too little clearance, especially on heavy stock, will cause a double breakout because of secondary shearing and the work will have a very rough edge. Too much clearance is a direct cause of burrs. Clearance in a round die is $\frac{1}{2}$ the difference between the diameter of the punch and die or, in a die of irregular shape, it is the distance between the punch and die on any side.

The rule for cutting clearance for mild steel is $1/10$ of the metal thickness and for hard steel $1/4$ of the metal thickness. For heavy gages, 0.001 in. clearance on each side of the blank for every $1/64$ in. of metal thickness can be used. Both cutting clearance and shear have a direct bearing on the size of press to be used.

Shear will reduce the amount of resistance which the punch encounters at any moment during the blanking operation, and this decreases the size of press required. Shear is obtained by grinding either the die or the punch with high and low points.

The proper depth of shear in a die is from 1 to $1\frac{1}{2}$ times the metal thickness. The stock immediately around the perimeter of the die is distorted by the shear and must not distort the stock adjacent to the next blank. When the blank must be flat, shear is on the female die; when the sheet must be flat, shear is on the punch.

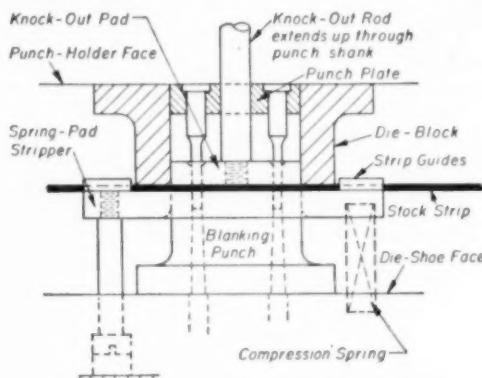


Fig. 3. Compound Blank and Pierce Die

locations and width tolerances vary $\pm 1/32$ in. An example is a short strap with two holes. The stock would be sheared $\pm 1/32$ to a width equal to the length of the strap and the straps would be cut off to their proper width by the cut-off die after holes and end shapes have been punched.

Heavy-gage stock has camber and twist when sheared to size, because of angularity of the shear blades. The cost of removing twist by roller leveling is still cheaper than the added cost of scrap produced by a compound die and is much cheaper than using band edge or mill edge stock.

The "pierce, cut-off and form" die is similar in operation, but also includes

Burrs are caused by too much clearance, insufficient shear, and dullness of the tool. Dullness will be a problem if die maintenance is poor, but it must be expected and allowed for in choosing the size of equipment.

Piercing

Piercing is cutting a hole in a piece of metal. It is usually done in conjunction with some other operation, such as blanking or trimming, but sometimes a secondary operation is necessary to avoid deforming or mislocating of holes during bending and forming. Piercing may also be a secondary operation when there are so

many holes that the required tool would be too weak if all were punched with one die.

In planning secondary piercing operations involving many holes, the required pressure may have to be reduced by using shear on the punches, by staggering their lengths equal to the depth required to shear the slug. To prevent punch breakage, a guided stripper and possibly a four-post die set may be required. Pressure could be reduced further by increasing the cutting clearance, provided more burr is allowable.

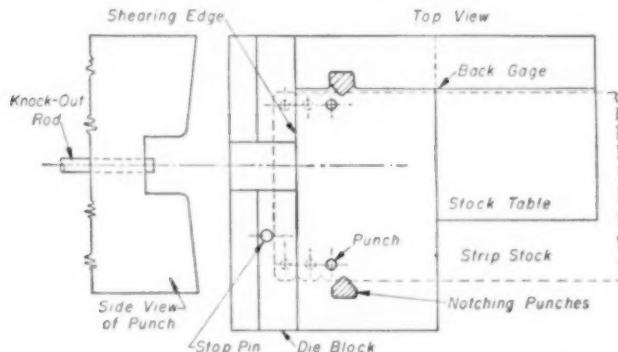


Fig. 4. Pierce, Cut-Off and Form Die

Dies can be more quickly repaired if punches and die buttons are removable.

Piercing of holes with straight side walls in heavy stock for later tapping can be a special problem. Cutting clearance between punch and die buttons must be less than standard. In addition, the punch itself is held in a sleeve or ferrule and also guided in a hardened bushing in the stripper, the stripper itself being guided by separate guide pins and bushings. In this manner a straight clean hole can be pierced with practically no breakout in stock thicker than about 0.030 in., and where diameter is only $\frac{1}{2}$ the thickness.

Trimming

Trimming is a secondary operation which can be combined with one or more other operations such as piercing, stenciling, embossing or flanging.

A "flange trimming die" is used to trim continuous irregular flanges of drawn shells or parts having two sides to be trimmed. This tooling is similar to the regular compound blank and pierce die shown in Fig. 3, where the female die is above and the punch, which pilots the part, is below. The trim scrap surrounds the punch and is usually cut apart between chisel-shaped scrap cutters and the female die. For long life and trouble-free production the scrap cutters should be far enough below cut edge to leave two or three pieces of scrap intact on the punch or lower die so that only the bottom piece will be severed as each new piece is trimmed, and neither the female die nor the scrap cutters will be dulled or sheared.

A "cam trimming die" is used to trim side walls with a square cut in close length-tolerance from the base. This die is constructed so that a form or matrix locating the part contains a fixed cutting edge, past which a shear blade or slide is moved by mating cams

on the upper die, thus shearing off scrap which then drops down through the die.

"Pinch trimming dies" are used for drawn shells (round, square, or rectangular) and in combination with other operations such as blanking and drawing when the size and shape of the part is favorable.

The pinch trim die shown in Fig. 5 will trim a shell with straight side walls, held to close tolerance for length. It can produce a nearly square cut which will be clean and without visible

shaved and blanked from the same side, to prevent an objectionable burr on the rounded edge.

If one shave is not sufficient to square an edge or hole, especially in soft metal, the second shave should remove less metal than the first.

Allowances for shaving differ greatly but a good standard for the material removed in the first shave would be:

Stock Thickness, gage	in.	Allowance per Side
20 gage	0.0359	0.005 in.
16	0.0598	0.007
13	0.0897	0.010
11	0.1196	0.012
$\frac{1}{4}$ in.	0.250	0.025

Bending and Forming

Small parts which require several forming operations can be shaped in one die set but some parts are larger than existing equipment. If a large part is not of such shape that it must be formed all at once, the method of manufacture depends largely on costs and the determining factor is quantity. For example, if a large flat panel requires a bend at either end, a large die and a large press are required to make both bends simultaneously in a single operation with one handling. An alternate method would be to form each bend separately with a standard V-die in a press brake; there would then be no tooling cost, but two slow operations and two handlings would be necessary. To determine the cheaper method of producing the part, the detailed cost of the special die and the operation of a larger, more expensive press must be compared with the extra cost of labor to form the part in a press brake.

When the metal is thick enough to resist wrinkling, a stamping can be formed in one operation in a simple solid-type die. Thinner metal can be formed in one operation if it can be controlled by a pressure-pad; otherwise, two or more dies will be required.

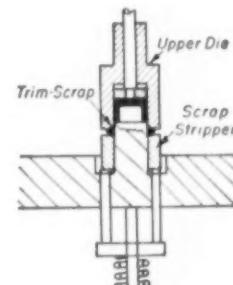


Fig. 5. Pinch Trim Die

The strength of a die should always be considered when operations are being laid out. It may be practical to blank and draw a shallow thin-walled shell from soft steel in one operation in a die of this type. The thickness of the combination blanking and drawing die-ring is approximately equal to the depth of the part. If the metal to be formed is thick or strong it would be necessary to cut the blank in one die and form it in another.

A single ear, lug, flange or other simple bend can be formed through

approximately 160 deg in one operation in a simple V-die fitted with a locating nest. In 90-deg V-dies, the die opening must be at least 8 times the stock thickness (Fig. 6). Multiple bends also can be formed in one operation in either or both directions but not re-entrant to the direction of stroke. One or more acute bends can be formed in a multiple bending die, but such dies are very expensive because swinging arms or cams, and often collapsible punches, must be used (Fig. 7).

Parts that have a formed flange or shape along a curved break-line often require additional operations because the metal may get out of control and wrinkle or fracture. The need for additional corrective operations to produce a part of the required accuracy

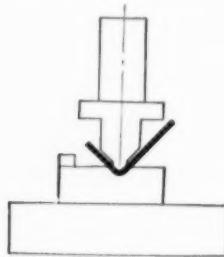


Fig. 6. V-Die

may often be avoided by overbending. In many parts, particularly heat treated parts, flattening, restriking or sizing is necessary to bring them back to size and shape.

In certain types of bending and forming dies which perform two or more operations in one press stroke, the pressure-pad must remain in its up-position until a portion of the part has been formed. If the air cushion does not have the capacity to hold the pad up while the part is being formed, each operation must be done in a separate die.

The available presses and allied equipment often determine how a stamping should be made. If a press does not have either space to accommodate a large die or the capacity to close it and form a part in one operation, the work must be divided between two or more smaller dies. Sometimes the press may be large and strong enough but the stroke will be too short to remove the finished part from the die. This also necessitates more than one operation. If several operations are combined in a single die which uses cams or other special devices to do a portion of the work, a press of longer stroke than otherwise is usually needed.

Deep Drawing

Deep drawing is the forming of cup-shaped parts from sheet metal by controlled plastic flow. Deep drawing tools redistribute the metal while limiting its change in thickness (in severe draws) to slight thinning at the closed end and thickening at the open end. Draws of any depth using these principles of controlled plastic flow may be called deep drawing.

Deep drawn parts are made in a wide variety of sizes and shapes, from fenders to thimbles, using metal ranging from foil to 1-in. plate. The fun-

damental principles are the same and the limitations of the process are usually those of available presses.

Cylindrical parts are the easiest to draw, but oval, square, rectangular and polygonal shapes can be readily handled. It is best to have corner radii 4 to 10 times the wall thickness but smaller radii and even sharp corners can be produced by redrawing, striking or sizing.

Typical operational samples for a single deep drawn part are shown in Fig. 8.

Allowable Reduction. The severity of a draw is sometimes expressed by the ratio of depth of cup to diameter of cup. A more useful and more generally accepted measure is the percentage reduction from the diameter of the blank to the diameter of the cup. Thus, a cup of 3-in. diam drawn from a blank of 5-in. diam represents a percentage reduction of 40%. The maximum reduction practical per operation is approximately 45% with optimum conditions of tooling and metal.

A Primary Draw starts with a flat blank and forms a cup (as in Fig. 8). In all draw work, the die radius over which the metal flows is of utmost importance. Under average conditions it is 4 to 6 times the metal thickness. For free flow it is also necessary to provide a clearance between the punch and die about 10% greater than the thickness of the blank.

A Single-Action Draw is the cheapest and simplest type; a descending punch forces the drawn cup entirely through the die in a single-action press (Fig. 9). The cup is stripped from the punch on the upstroke. Since the outer periph-

draws. The die is mounted on the bed of the press and the cup can usually be drawn entirely through the die, so as to fall on a conveyor below. Double-action operations are well suited to difficult draws and parts of large area where the pressure on the blank holder may run to fairly high tonnages. Some shops prefer double-action presses even for light and medium drawing because of the relative simplicity of tooling, although the initial cost of the presses is higher than for single-action presses.

Redrawing Operations are necessary on parts which cannot be fabricated in a single draw. The maximum reduction practical with one redrawing operation is approximately 30%, with optimum conditions of tooling and metal. Successive reductions are usually scaled down from this amount. A typical progression might be 30%, 25%, 22%, 18%, and 15%.

In a Single-Action Redraw the descending punch draws the cup into the die, which reduces the diameter. Tools are the simplest possible for redrawing, and production speeds are high.

Single-Action Redraw With Pressure Sleeve is used when the proportions of the redraw are too severe to permit satisfactory production as above and it is necessary to add a pressure sleeve, which fits inside the primary cup and around the redraw punch. The pressure sleeve acts like the blank holder in a primary draw, to prevent wrinkling and to control the plastic flow. It may derive its pressure from springs or rubber, but an air or hydraulic cushion gives much more satisfactory results. The usual mounting of the die elements produces an inverted cup, which must

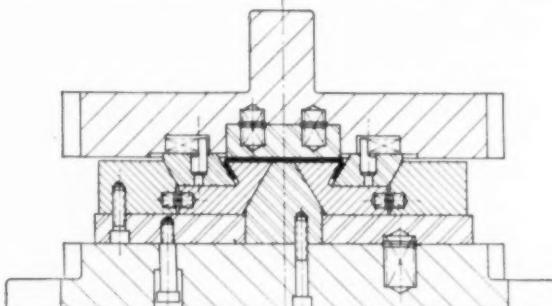


Fig. 7. Multiple Bending Die with Cam and Collapsible Punch

ery of the blank is not confined, it tends to form wrinkles which may be ironed out between the punch and die as the draw is concluded. The lighter the wall thickness and the deeper the cup, the greater the tendency to wrinkle.

Single-Action Draw With Blank Holder. When the metal is too thin or the cup too deep for fabrication as above, a blank holder or pressure ring must be added (Fig. 10). The pressure of the blank holder may be produced by springs or rubber on light work, or by an air or hydraulic cushion on heavier work. The cups must be ejected back through the die on the upstroke of the press. This method is useful for a wide variety of work, including some rather difficult shapes.

In a Double-Action Draw, the blank holder is actuated by the press, rather than by springs or a cushion, for better control of pressure, especially on deep

be ejected or removed from the tools.

In a Double-Action Redraw the pressure ring is mounted on the blank holder slide and is actuated mechanically or hydraulically like the blank holder described under primary draws. The cups are drawn entirely through the die and are stripped from the punch on the upstroke.

Thin parts are sometimes severely redrawn by turning the cups inside out in a double action reverse redraw as shown in Fig. 11.

Partial Draws and Necking Operations. When a primary draw is set so the blank is not drawn entirely through the die, the cup will have a flange around the open end. If the combined area of the required cup and flange result in a blank within the maximum limit as determined by the percentage reduction from blank diameter to cup diameter, only one operation is re-



Fig. 8. Sequence of Operations in Deep Drawing. (1) Blank. (2) Double-action draw. (3) Double-action redraw. (4) Reverse draw. (5) Neck. (6) Strike. (7) Trim

quired. If this limit is exceeded one or more redraws must be added. Partial redraws can be added to reshape the cup portion only, leaving the outside diameter of the flange unchanged. By this means almost any desired proportions of cup and flange dimensions can be produced.

Ironing is a specialized type of redrawing in which the die elements are designed to reduce the wall thickness of the shell. Slight reduction in inside diameter permits the punch to enter



Fig. 9. Single-Action Draw

the starting cup freely. The wall thickness of the final part is determined by the clearance between punch and ironing ring.

Ironing may be used for the following reasons:

- 1 To produce shells having a bottom thicker than the side wall
- 2 To meet accurate tolerances of the wall thickness
- 3 To produce tapered walls using a tapered ironing punch
- 4 To produce steps in the wall thickness by using several ironing operations, each producing a reduction in the wall thickness and outside diameter.

Striking or Sizing is an additional operation needed if sharp corner radii, indentations, ribs or accurately coined dimensions are required. Such operations are not incorporated in the drawing operations because best results are obtained when there is free plastic flow around large radii and smooth contours. Thus, drawing pressures are minimized and high-quality parts are produced, free from scoring.

Combination Operations. Many combinations of the various drawing operations are successful; others are of doubtful advantage. Frequently two rapid, trouble-free operations are more practical than one complicated combination.

Blank and Draw. In this arrangement the blank holder or pressure ring also acts as a blanking punch. This combination is common and practical. It is also sometimes feasible to add a piercing operation, although disposal of the slug may be difficult.

Double Draws or successive draws are possible, one under the other. The disadvantages are the long stroke required, the difficulty of lubricating the second draw, and of set-up and main-

tenance. Draw-and-iron and double ironing operations are similar to double draws and have much the same advantages and disadvantages.

Draw Strike tools may be designed to strike a heavy blow on some portion of the cup at the bottom of the stroke—for example, to form indentations, bosses or ribs on the closed end.

Proper Lubrication can make the difference between success and failure in severe draws. Mineral oil or lard oil are satisfactory for moderate reductions on thin metal. On more severe draws, tallow or soap should be used. On the deepest draws, high-pressure lubricants are required and pigmented or chlorinated compounds are often helpful. Dry-film lubricants have been effective in many types of draw work and can be removed easily by hot water.

Work Hardening and Stress Relieving. The hardening of work metal which occurs during deep drawing limits further reductions. If the maximum reduction is made on the primary draw,

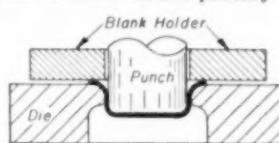


Fig. 10. Single-Action Draw with Blank Holder

more than one moderate redraw is impractical unless the steel is annealed at 1150 to 1250 F (for low-carbon sheet). The time-temperature combination should be selected so as to avoid excessive grain growth in the closed end of the drawn cup, which usually has had the critical amount of deformation that would lead to this condition.

Cold Extrusion

In cold compression forming, cold metal is forced to flow plastically into a die cavity of the desired shape. Cold extrusion, swaging and coining are all within the scope of this broad definition. Only cold extrusion is considered here; swaging and coining are described on pages 35 and 42, respectively, of the 1948 Handbook.

Cold extrusion involves either forward or backward displacement, or both, under steady and nearly uniform pressure.

Forward displacement of metal is in the direction of punch travel, as shown in Fig. 12(b). The die recess is just large enough on one end to receive the starting slug and on the other end has a smaller orifice of cross section like the desired part into which or through which the metal is forced.

Backward displacement from a closed die is in the direction opposite to punch travel, Fig. 12(a). Parts are often cup-shaped and have wall thickness equal to the clearance between punch and die.

In combined forward and backward displacement, some of the metal flows forward and some of it backward, as shown in Fig. 12(c). The punch and die (with closed bottom) prevent flow beyond the desired shape of the finished product.

(Coining involves displacement of metal radially to fill a die cavity, and swaging involves radial displacement by hammers without complete circumferential confinement. Impact extrusion is the displacement of metal by the very rapid application of pressure with collision force.)

Steels having up to 0.30% C are commonly shaped by cold extrusion. Severity of the operation determines the need for intermediate annealing. The most favorable grain size and structure are obtained by spheroidizing.

Lubricants that do not become embedded in the die surface are of utmost importance. Phosphate coatings are used specifically for this purpose; sometimes oils are used in addition for the more severe applications.

Dies must be exceptionally sturdy and must have built-in alignment to insure accuracy and to equalize the high forces inherent in the process. Dies must be adequately supported to prevent any expansion that would break them. The grind-fitting of die rings, tapered on the outside, and holding

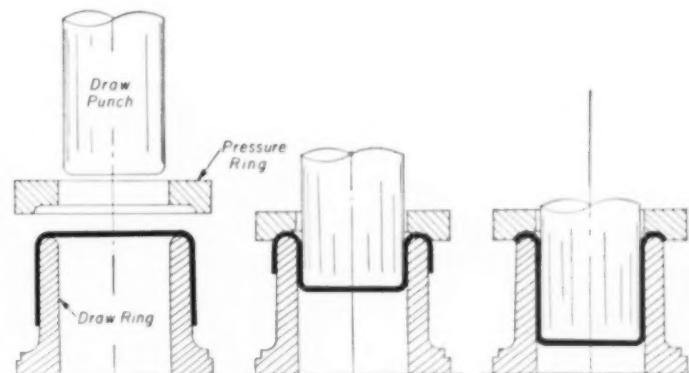


Fig. 11. Double-Action Reverse Draw

them with clamping rings are well worth the cost. Selection of die materials is discussed on page 29.

Equipment used for compression forming requires much more power than for deep drawing parts of comparable size by conventional methods. This greater power requirement and the advantage of long strokes with uniform speed and pressure, and safety from overload favors the use of hydraulic presses. The slower speed of the presses is more than compensated by the fewer operations required.

Limitations of large-scale commercial production of compression formed parts rest mainly in the dies, which cost about 50% more than dies for making similar parts by a conventional drawing process. Facilities capable of extruding cylinders approximately 24 in. deep and up to 6-in. diam at the required 2000 to 3000-ton pressures are currently available. Parts of irregular shape may require high development cost.

Advantages. Because parts are made from slugs accurately sawed from round bars, trim scrap is negligible. Parts may be made of inexpensive low-carbon steel and cold worked to tensile strengths in excess of 100,000 psi and yield strengths in excess of 90,000 psi for steels of 0.15% C or less after 75% reduction by cold extrusion. The finished part usually acquires the accuracy and mirror finish of the die surfaces, and little or no machining is required.

Utilization of Metal

In producing a part for the lowest possible cost, the most efficient utilization of sheet metal may dictate the operations to be used. Sometimes a complicated part can be made at less cost by joining two simple shapes. Formability requirements for the steel sometimes can be reduced by slight changes in die contours, press speeds or (in high production) by adding more stages in the forming operation so that less expensive metal can be specified.

Secondary parts can be made from the waste blanked from larger parts. This can reduce costs but must usually be provided for in the original tool planning, for greatest economy. Slight redesign of the part for better nesting of blanks may permit the use of narrower stock and reduce scrap. If the blank is triangular, the strip should be run through the die twice, reversing the blank in the strip in the second pass.

Irregular blanks should be nested or interlocked for greatest economy. With round blanks, at least 8% can be saved by running a double width of stock with the second row of blanks staggered with the first. The possible cost savings of multiple blanking from coil stock to produce two or more parts per stroke should always be examined.

Purchasing involves several factors important in the planning of processing. For instance, temper must be specified with regard to both the engineering properties of the metal and the tolerances on bends. Standard practice and product classifications are subject to change. The various sections of the AISI Steel Products Manual deal au-

thoritatively with different flat rolled steel products, as follows:

- Sec 11—Carbon Steel Sheets.
Hot Rolled or Cold Rolled
- Sec 12—Hot Rolled Steel Strip
- Sec 13—Cold Rolled Steel Strip
- Sec 14—Tin Mill Products
- Sec 24—Stainless and Heat-Resisting Steels

Tolerances on various attributes of the product are related to size throughout each section of the manual, as indicated in Table I.

The "Manufacturers' Standard Gage for Steel Sheets" is based on nominal increments of the weight (in ounces per square foot) of a steel plate 1 in.

be specified to the fourth decimal place even though steel is not rolled to that limit of accuracy. The "thickness ordering range" within which the specified thickness falls then determines gage ordering limits, gage and width size extras and standard plus-or-minus tolerances which apply on the thickness specified.

By paying added premiums for operations such as stretcher leveling or resquaring or for restricted thickness tolerance, steel can be ordered to width, length, flatness or thickness limits closer than standard for the product in question. For exact details, refer-

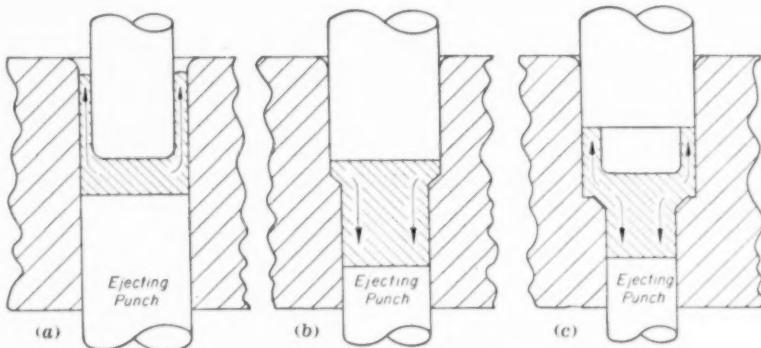


Fig. 12. Forward, Backward, and Combined Forward and Backward Displacement in Cold Extrusion

thick by 12 in. square weighing 41.820 lb, rather than by increments of dimensional thickness. Thickness should always be specified in decimals. Sheets specified to a Manufacturers' Standard Gage number are produced to the inch equivalent for that gage number.

"Thickness ordering ranges", extending about equally above and below the nominal gage size, are used for determining product classification, tolerances and pricing extras which apply to the item ordered. When sheet steel is ordered, a definite thickness should

ence should be made to the applicable tables of the Steel Products Manual listed in Table I.

The variety of steels that may be chosen to run a given part is limited when quantity is less than a mill order. This quantity varies from year to year and depends on the steel being ordered. Minimum mill orders are usually about 5 tons for carbon steel sheet and about 3 tons for carbon steel strip. Orders for smaller quantities of stainless and heat-resisting steels can frequently be negotiated with the mills.

Table I. Index to Tolerance and Limit Tables in Indicated Sections of AISI Steel Products Manual, for Flat Rolled Steel

Condition ^(a)	AISI Sec No. ^(b)	Thickness (c)	Crown (d)	Camber (e)	Table Number in Indicated AISI Section Where Tolerances and Limits May be Found				
					Width (f)	Length (g)	Flatness (h)	Width (g)	Length (g)
Carbon Steel Sheets									
HR.....	11	4	..	8	5	10	6	10	9
CR.....	11	13	..	17	14	19	15	19	18
Carbon Steel Strip									
HR.....	12	1	2	5	3	..	4	..	..
CR.....	13	1	2	7	3, 4, 5	..	6	..	..
Tin Mill Products									
.....	14	7	..	..	..	..	..	..	..
Stainless Steel Sheets (hot and cold rolled)									
.....	24	40	..	44	42	41	43	41	45
Stainless Steel Strip									
HR.....	24	48	49	..	50	..	..	..	..
CR.....	24	51	52	56	53, 54	..	55	..	..

(a) Condition of steel: HR, hot rolled; CR, cold rolled. (b) Section number of the AISI Steel Products Manual where table referred to can be found. (c) Deviation from theoretical dimension, excluding "crown". (d) Variation in thickness from edge to center. (e) Deviation of edge from straight line. (f) Not stretcher leveled or resquared. (g) Stretcher leveled

Machining of Steel and Cast Iron

By the ASM Committee on Machining

THIS ARTICLE concerns the production planning and engineering aspects of the machining of ferrous metals. It deals briefly with the basic happenings in chip formation, the cutting tool, metallurgical aspects of the work material in relation to machining, the power required, the cutting fluid, and finally the way in which all these factors may be correlated to obtain lowest cost production. While the discussion applies largely to single-point tools, the basic principles presented apply also to other types of machining operations.

The Metal Cutting Process

Chip Formation. The mechanism of the chip-forming process is identical in all metal cutting operations, for example, turning, milling, broaching, grinding and drilling. In every operation, a cross section through chip, tool and work piece, perpendicular to the cutting edge, appears somewhat as in the diagram, Fig. 1, or the photomicrograph, Fig. 2. The face of the tool may either be inclined backward from the cutting edge, as in Fig. 1, to provide

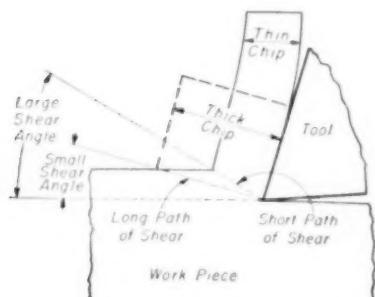


Fig. 1. Diagrammatic Cross Section through a Chip, Tool and Work Piece with Shear Angle Indicated

the conventional positive rake, or be inclined forward from the cutting edge, as in Fig. 2, to provide negative rake.

Regardless of the machining operation, only three types of chips are normally found: type 1, the segmental or discontinuous-type chip; type 2, the continuous chip with no apparent built-up edge; type 3, the continuous chip with built-up edge.

These three types are illustrated in Fig. 3. The basic mechanism in each case is the same—the chip is formed by plastic deformation in a narrow zone (substantially a plane) leading from the cutting edge to the work surface and forming an angle with the tool path (known as the shear angle ϕ) which varies over a wide range under various cutting conditions. As the chip escapes by sliding over the face of the tool, it encounters high frictional resistance. The degree of frictional re-

sistance and angle of the tool face, together with the physical properties of the material being machined, determine the type of chip.

Type 1 Chips are generated under conditions which produce intermittent rupture on the shear plane as with

with poor finish because fragments of the built-up edge are constantly being torn off, hundreds and even thousands of times per second, as part of the machined surface. A fragment of built-up edge escaping with the machined surface may be seen in the micrograph of the type 3 chip in Fig. 3. The built-up edge may be minimized by using the

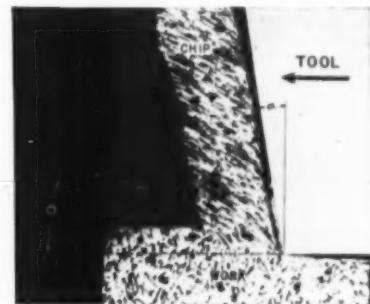


Fig. 2. Photomicrograph of a Cross Section through Chip, Tool and Work Piece

highest economical cutting speed, high positive rake angles, applying effective cutting fluids, using free-machining steels or steels of low strain hardenability and, where possible, decreasing the thickness of the chip by reducing the feed increment or by increasing the side cutting edge angle. For details on the mechanics and geometry of these three types of chip, the reader may consult the first five references on page 151.

Type 2 Chips are smooth continuous chips with no apparent built-up edge. They are produced under conditions of low friction with a ductile metal when machining at high speed, as when using carbide tools. They may also be produced at low cutting speed when using a very effective cutting fluid. This is the ideal type of chip for good surface finish and low power consumption, and usually also for optimum tool life.

Type 3 Chips normally result from machining a ductile metal with high speed steel tools at conventional cutting speeds. They are similar to type 2 chips except for the presence of the built-up edge, which is a more or less stagnant mass of chip material which adheres to the tool face whenever the friction force is high enough to allow the body of the chip to shear past it as it flows away, up the tool face.

Type 3 chips are always associated

with poor finish because fragments of the built-up edge are constantly being torn off, hundreds and even thousands of times per second, as part of the machined surface. A fragment of built-up edge escaping with the machined surface may be seen in the micrograph of the type 3 chip in Fig. 3. The built-up edge may be minimized by using the

Chip Geometry and Mechanics. The importance of the shear angle may be appreciated from a study of the micrograph, Fig. 2, and the diagram, Fig. 1. From the latter it may be seen that if the shear angle is small, the path of shear will be long, the chip will be thick and the force to shear will be high, which constitutes poor chip formation. This usually results in higher temperatures and a shorter tool life. Conversely, if the shear angle is large, the path of shear will be shorter, the chip will be thinner and the force required to remove the same layer of metal will be less. This constitutes effective chip formation.

The force system for the simplified case, where the cutting edge of the tool is straight and perpendicular to the direction of travel of the tool, is shown in Fig. 4. One set of forces acts between chip and tool at the bearing area between these two, and is made up of the friction force F which resists

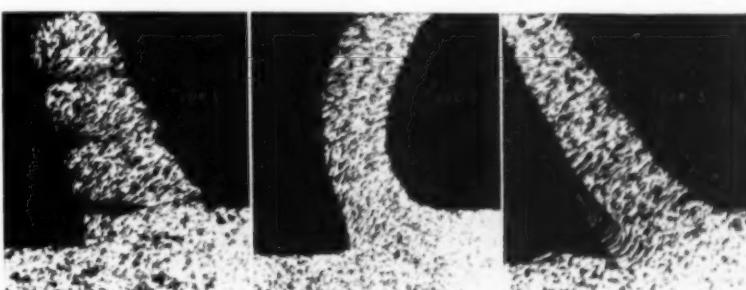


Fig. 3. Three Types of Chip. Type 1, segmental or discontinuous; type 2, continuous without a built-up edge; type 3, continuous with a built-up edge

Supplements the articles on pages 360 to 371 of the 1948 ASM Metals Handbook

the sliding of the chip up the tool face, and its normal force N . The ratio of F/N (or $\tan \gamma$) is the coefficient of friction at the chip-tool interface. A second set of forces acts between the chip and work at the shear plane, and is made up of the shearing force F_s and its normal force F_n . These two sets of forces are the only forces acting on that body; thus they must balance each other. The equal and opposite resultant forces R and R' hold the chip in stable mechanical equilibrium.

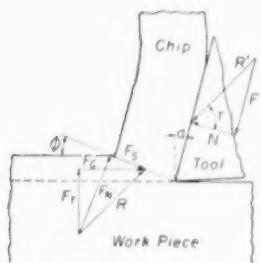


Fig. 4. Schematic Diagram of Forces Acting on a Chip

It should be noted that under practical cutting conditions the component F_s is usually very large. This indicates that the metal being displaced along the shear plane is under a high compressive stress and accounts for the large deformation which the metal may undergo along the shear plane without fracture, in producing continuous chips of types 2 and 3. Since the set of forces acting at the shear plane is balanced by that acting at the tool face, any change in the friction conditions, or the rake angle of the tool face (α), will affect the angle of the shear plane. Mathematical analysis of this interrelationship³ has resulted in the following equation:

$$\text{Shear angle } (\phi) = \frac{C - \tau + \alpha}{2}$$

where C is a constant the value of which depends on the material being machined. In the case of steel and cast iron, C usually ranges from about 70 to 90 deg, while τ (the friction angle) varies from about 30 to 50 deg. To a first degree of approximation, this relationship agrees well with values derived from actual metal cutting tests. Thus, for any given material, an increase in the rake angle or a decrease in the coefficient of friction will result in an increase in the shear angle, and will produce a thinner chip.

The actual value of the shear angle during a machining operation may be calculated from the equation:

$$\tan \phi = \frac{(t_1 t_2) \cos \alpha}{1 - (t_1 t_2) \sin \alpha}$$

where t_1 and t_2 are the values of the thickness of the chip before and after its removal from the work piece. The ratio t_1/t_2 is known as the cutting ratio. This is also equal to the length of the chip divided by the length of the tool path which produced it.

Cutting Tools

Tool Materials. Four general types of tool materials are used for all classes of cutting tools: carbon tool steel, high

speed steel, cast cobalt-base alloys, and cemented carbides.

A thorough discussion of *carbon tool steels* and *high speed steels* for metal cutting tools is given in the ASM publication, "Machining — Theory and Practice". A further discussion of this subject is given on page 23 of this Supplement.

The Cast Cobalt-Base Tool Materials, consisting of various combinations and compositions of cobalt, chromium, tungsten, molybdenum and tantalum, occupy an intermediate position between the high speed steels and the cemented carbides, with respect to hardness, toughness and wear resistance. They are described on page 63 of the 1948 Metals Handbook.

Cemented Carbides are manufactured in two primary types, one for machining nonferrous materials and cast iron, the other for steel. Each has several grades, varying in chemical composition, grain size and performance characteristics. The combination of properties possible with various mixtures of tungsten, tantalum, columbium and titanium carbides, having metallic cobalt as the binder, has resulted in a complicated variety of grades available from the various manufacturers. The grades for machining cast iron are usually straight tungsten carbide and cobalt mixtures, varying in grain size

Tool Angles and Nomenclature. Basic elements and nomenclature of a single-point tool are shown in Fig. 5. Standard designations of relief angles, cutting edge angles and rake angles are strongly recommended.

It is beyond the scope of this article to recommend tool angles for all possible combinations of microstructure and hardness, for all tool materials, on all types of machining operations. However, some general examples may prove useful as a starting point, particularly for milling and also for turning when standard tools lack optimum performance for high-production work.

One such example covering suggested rake and relief angles for the turning of soft steel is given on page 368 of the 1948 Metals Handbook. Examples of cutter angle combinations that have proved satisfactory for certain milling operations with carbide cutters are listed in Table I.

The geometrical relationship between tool face and work is identical in face milling and turning operations. Axial rake, radial rake and corner angle in face milling are respectively equivalent to back rake, side rake, and side cutting edge angle in turning. These are the angles by which the relationship of cutting edge to work is usually defined.

The most significant angle in any machining operation, however, is the

Table I. Satisfactory Cutter Angles for Carbide Milling

Type of Steel Work Material	Axial Rake, deg	Radial Rake, deg	True Rake, deg	Corner Angle, deg	Inclination, deg
Slab Milling					
Low-Carbon and Annealed Alloy ...	5	-5	-5	..	..
Hardened Alloy	10	-10	-10	..	..
Slotting and Sawing					
Low-Carbon and Annealed Alloy ...	0	-5	-5	..	..
Hardened Alloy	0	-10	-10	..	..
Face Milling					
Low-Carbon and Annealed Alloy ...	5	-12	-5	45	12
Hardened Alloy	5	-18	-10	45	16

and cobalt content. Fine grain sizes are harder than the coarse grain. In steel-cutting applications, additions of titanium and tantalum carbides decrease the cratering on the face of the tool caused by its intimate engagement with the flowing chip. These additions also increase red hardness up to 1800 F and help to prevent burning and to maintain the tool edge.

Tool hardness is usually a direct measure of probable tool life, but the danger of minute chipping of the cutting edge of the harder carbides also increases with hardness. The less the feed and depth of cut, with a commensurate increase in speed, the harder the carbide that can be used efficiently.

Frequently, physical requirements of the machining operation call for small tools or those with inherently weak design. Here the softer carbides must be specified to resist damage caused by deflection and chatter. Small radii or the use of coolants to carry away chips may rule out use of the harder grades of carbide.

Hardened steels, or those with relatively poor machinability, also require use of the "softer" grades of carbide. The same is true of fragile, coarse-grained or scaly stock, which may chip the harder grades.

"true rake" angle. As indicated by the equation for shear angle in terms of rake and friction angles (see col 1), the true rake angle directly affects the

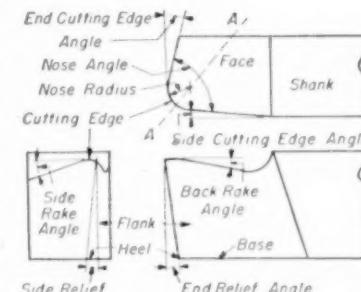


Fig. 5. Nomenclature of a Ground Right-Cut, Single Point Tool with a Straight Shank (American Standards Association)

shear angle in the chip forming process, and therefore greatly affects the tool forces, power and temperature. The larger the positive value of the true rake angle, the lower the force. It is limited in magnitude, however, by the

strength required of the tool for any particular machining operation.

In milling, the true rake angle is the resultant of the axial rake, radial rake, and corner angle. In turning, therefore, it is the resultant of back rake, side rake and side cutting edge angle.

Figure 6 shows the geometrical arrangement of the various rake angles. Each of the rake angles is measured with respect to a reference plane which, in milling, passes through the axis of cutter rotation and the point of the tool. In turning, the reference plane passes through the axis of the work piece and the point of the tool. True rake (by definition) is measured in a plane perpendicular to the projection of cutting edge on reference plane.

The angle of next importance in machining is *inclination*. This is the angle which the cutting edge makes with the reference plane, which, by definition, is perpendicular to the direction of tool travel. Inclination determines the direction of chip curling. When the inclination is zero, chip flow is virtually in the plane of true rake.

Many combinations of axial rake, radial rake and corner angle other than those listed in Table I have also been successfully used in practice. The requirements for all types of machining operations are—first, to select a true rake large enough for the particular cutting conditions to provide effective chip formation, yet leaving an included angle for the tool sufficiently large to provide the required strength and heat conduction; second, to select an inclination for the cutting edge which will provide the desired direction of chip flow. In face milling, positive inclination directs the chip outward while negative inclination directs the chip toward the center of the cutter. In turning, positive inclination directs the chip toward the unmachined surface of the work, while negative inclination directs the chip toward the finished surface. A positive inclination is therefore generally desired.

The alignment chart, Fig. 7, is a semi-quantitative guide for the selection of true rake angles for various combinations of tool materials and common ferrous metals. The rigidity scale is a qualitative modifier of tool-work combination to allow for various degrees of rigidity in work, fixture or machine. Increased rigidity permits a positive increase in true rake.

After the suggested initial value for true rake has been selected from Fig. 7, it may be resolved into a tentative combination of rake and corner (or side cutting edge) angles by means of the chart, Fig. 8. The inclination provided by this combination may then be checked on the same chart.

Use of the charts, Fig. 7 and 8, may be illustrated by the following example. Assume a face milling operation on free-machining 1112 steel with a high speed steel cutter, with a setup and machine of average rigidity. On the alignment chart, Fig. 7, connect the high speed steel index with the upper end of the free-machining steel block as indicated by line A, and mark its intersection with the reference axis at point 1. Then connect point 1 with the "average rigidity" point by the line B and note its intersection on the true rake line at the recommended value of +15 deg.

Next, consult chart, Fig. 8. Usually

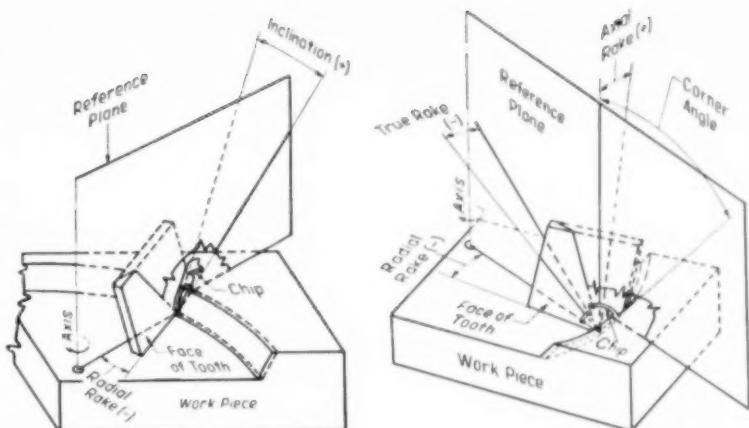


Fig. 6. Perspective Views of the Geometrical Relationships of Tool Angles and Reference Plane

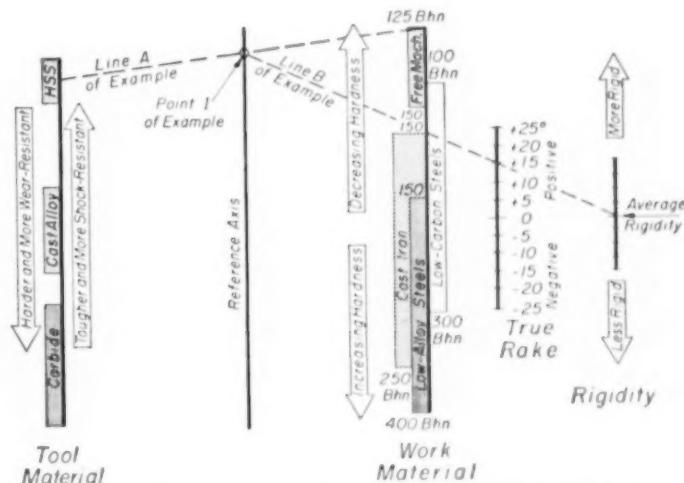


Fig. 7. Alignment Chart for the Approximation of True Rake

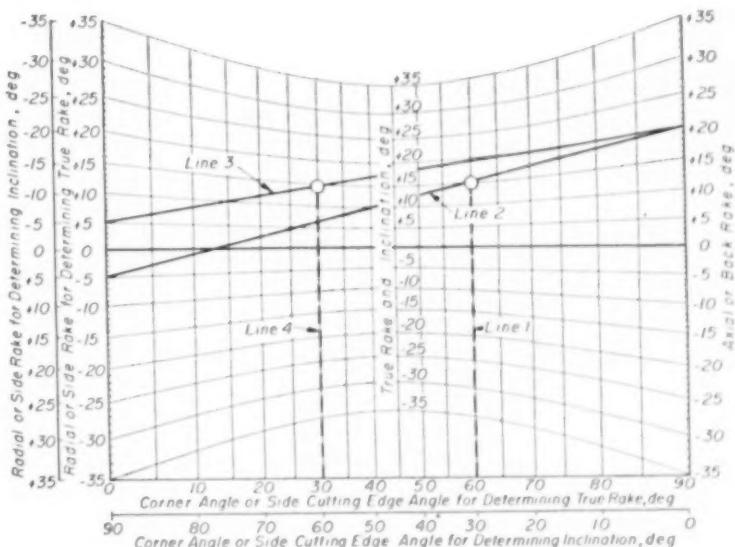


Fig. 8. Chart for Determining True Rake Components and Inclination of Teeth for Milling and Turning

one may begin with a desired or assumed value of corner angle, say 60 deg in this example. (For long tool life and maximum production, the corner angle should be as large as possible; if a chattering condition or heavy scale is encountered, the corner angle should be decreased.) Note the intersection of the "true rake" corner angle line 1 for 60 deg and the true rake line for +15

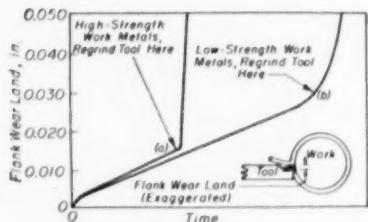


Fig. 9. Progression of Wear of Carbide Tools. High-strength metals are those of 300 to 500 Bhn; low-strength metals, less than 250 Bhn

deg. Through this point draw line 2 connecting some tentative value for axial rake (say +20 deg) with the radial rake scale, and read the value (-5 deg) for radial rake.

Next check this combination to find the corresponding inclination. Connect the +20-deg axial rake point with the -5-deg radial rake point by the line 3. (Note that the scale for radial rake is inverted for determining inclination.) Read inclination (+14 deg) at the intersection of this line with the vertical line 4 for 60-deg corner angle. If some other value of inclination were desired (so as to provide a different direction of chip flow) a different orientation of the line 2 through the +15-deg true rake line must be tried.

It should be noted that many different combinations of axial and radial rake angles will provide a given true rake with a given corner angle; however, only one combination will provide both a given true rake and a given inclination with a given corner angle.

Mode of Tool Failure. Tool life, with a given tool-work combination, is primarily a function of the temperature of the cutting tool. The relationship between tool life and cutting tool temperature has been found empirically by Schallbrock, Schaumann, and Walichs (Ref 7) to be of the form:

$$T t^n = K$$

where:

T = tool life, min

t = temperature at tool chip interface, deg Cent

n = an exponent, the value of which depends mainly on the tool form and tool material

K = a function of speed, feed, depth, tool, work, and cutting fluid (a constant when all of these quantities are held constant)

According to the above authors, the exponent n normally has a value of about 20, with high speed steel tools, and about 10 for carbide tools. Exponents of this order of magnitude have also been found by other investigators. It is evident, therefore, that a very small change in tool temperature has a large effect on tool life.

Tools fail by mechanical abrasion, which may be caused by either excessive face wear (cratering) from abrasion by the chip, or flank wear from abrasion by the newly machined surface, or a combination of both. Usually the wear on one surface predominates. If flank wear is allowed to proceed too far, the tool will break or fail very rapidly because of the excessive heat generated when cutting clearance is decreased by wear.

Tool failure from excessive face wear, or cratering, usually occurs when the

increasing cutting speed, according to the following empirical relationship established by Taylor:

$$V T^n = C_t$$

where

V = cutting speed

T = tool life (cutting time before resharpening)

n = an exponent, which depends on tool and work materials, tool geometry and cutting fluid

C_t = a constant for constant feed, depth, tool, work and fluid

The above general relationship is valid for high speed steel tools, providing only that the speed is high enough to produce a normal, free flowing chip.

For carbide tools there is a point of reversal in the tool life curve below which the tool life is decreased by a further decrease in cutting speed. The point of reversal may be as high as 300 fpm but is usually less than 150 fpm. Tool failure below this point is usually a chipping process, instead of the normal abrasive wear.

High speed steel tools, cutting ductile metals at moderate speeds, usually fail by cratering on the face.

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tool face temperature is very high, or when the apparent pressure between the chip and tool is very great. Cratering usually begins some distance from the cutting edge. As the wear progresses, and the width and depth of the crater increase, the edge of the crater approaches the cutting edge until the latter fails rapidly under the applied load. The practical tool life, under these conditions, ends just before failure of the original cutting edge.

With carbide tools, which usually fail by flank wear, it is economical from the standpoint of reconditioning to consider the tool to have failed when the wear on the flank has reached a condition corresponding to (a) in Fig. 9, where the rate of wear begins to increase rapidly at a value of not more than 0.015 in. when high-strength metals such as quenched and tempered steel (300 to 500 Bhn) are being cut. For softer metals such as cast iron or annealed steel (under about 250 Bhn) the flank wear land should not exceed 0.030 in., which corresponds to point (b) in Fig. 9. The cutting tool should be resharpened before the flank wear is accelerated by chipping at (a) and (b). If the cutting tool is ground prior to this point of rapid wear, less chipping of the cutting edge will occur and a harder grade of carbide can be used at higher speeds. After a rapid initial tool wear due to minor abrasion of the cutting edge, normal wear proceeds until enough force is exerted on the flank of the tool to cause chipping.

This same method of determining useful tool life can be used also for high speed steel tools, but about twice as much flank wear may be tolerated before regrounding.

It has been found experimentally that, if all other conditions are kept constant, tool life will decrease with

Power Requirements

The power required to machine metal is often expressed in terms of specific power, W_n , which is the horsepower at the cutter required to remove a unit volume of metal in unit time (horsepower per cubic inch per minute). Average values of W_n for steel and cast iron, for various Brinell hardness numbers, are given in Fig. 10. The values given are for sharp tools and good cutting conditions; they should be increased up to 100% for poor cutting conditions such as the use of very fine feeds. The specific power is not greatly affected by cutting speed over the range of speeds normally used in practice, but decreases slightly at higher speeds. The tool material has virtually no effect on specific power. Cutting fluids will reduce power when used at slow speeds on ductile metals but have little effect on power at high cutting speeds or on brittle metals.

Net power, P_n , equals $U \times W_n$, where U is volume in cubic inches of metal

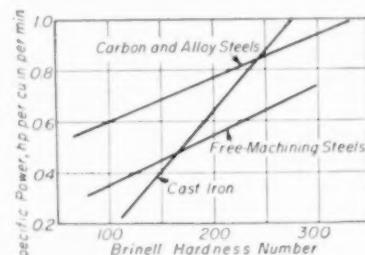


Fig. 10. Average Values of Specific Power, W_n , for Cutting Steel and Cast Iron

removed per minute. Gross power, P_g , the power developed by the motor driving the machine tool, is the sum of net power, P_n , and tare power, P_t . This tare power includes the power consumed in the feeding system, and frictional losses in the machine drive.

Reasonably accurate values of cutting force F_c (Fig. 4) may be obtained

from the equation $F_c = 396,000 W_n / fd$ by using the values of W_n presented in Fig. 10; fd (feed \times depth) is the cross-sectional area of the cut.

Work Metal and Tool Life

The machinability of the metal to be cut influences the type and number of machine tools, space and personnel needed to do a given job. The best source of machinability data is a tool life curve obtained under the manufacturing conditions in question. With the aid of such curves, production rates can be calculated and the required number of machine tools can be estimated.

When it is not feasible to run full tool life studies, other data may be used for rapid estimation. These include (1) chemical composition of the alloy, (2) hardness data and (3) data on microstructure such as microhardness and distribution of microconstituents. Usually all of these factors are influential and consideration of only one would be misleading. However, in cast iron, microstructure is the most important of the three.

Gray Iron. The important elements present in unalloyed gray iron are carbon, silicon, manganese, sulfur, and phosphorus; these elements and the rate of cooling control the microconstituents identified in Fig. 11.

The most important microstructural effects in the machinability of gray iron are: (1) the more ferrite the better the tool life, (2) the coarser the pearlite spacing the better the tool life, (3) the more iron carbide the poorer the tool life; even small percentages (5%) of the very hard iron carbide in massive form are detrimental; areas containing large percentages will cause tool failure almost instantly. Flash and other chilled sections of iron castings are really white cast iron, rather than gray, and are essentially unmachinable.

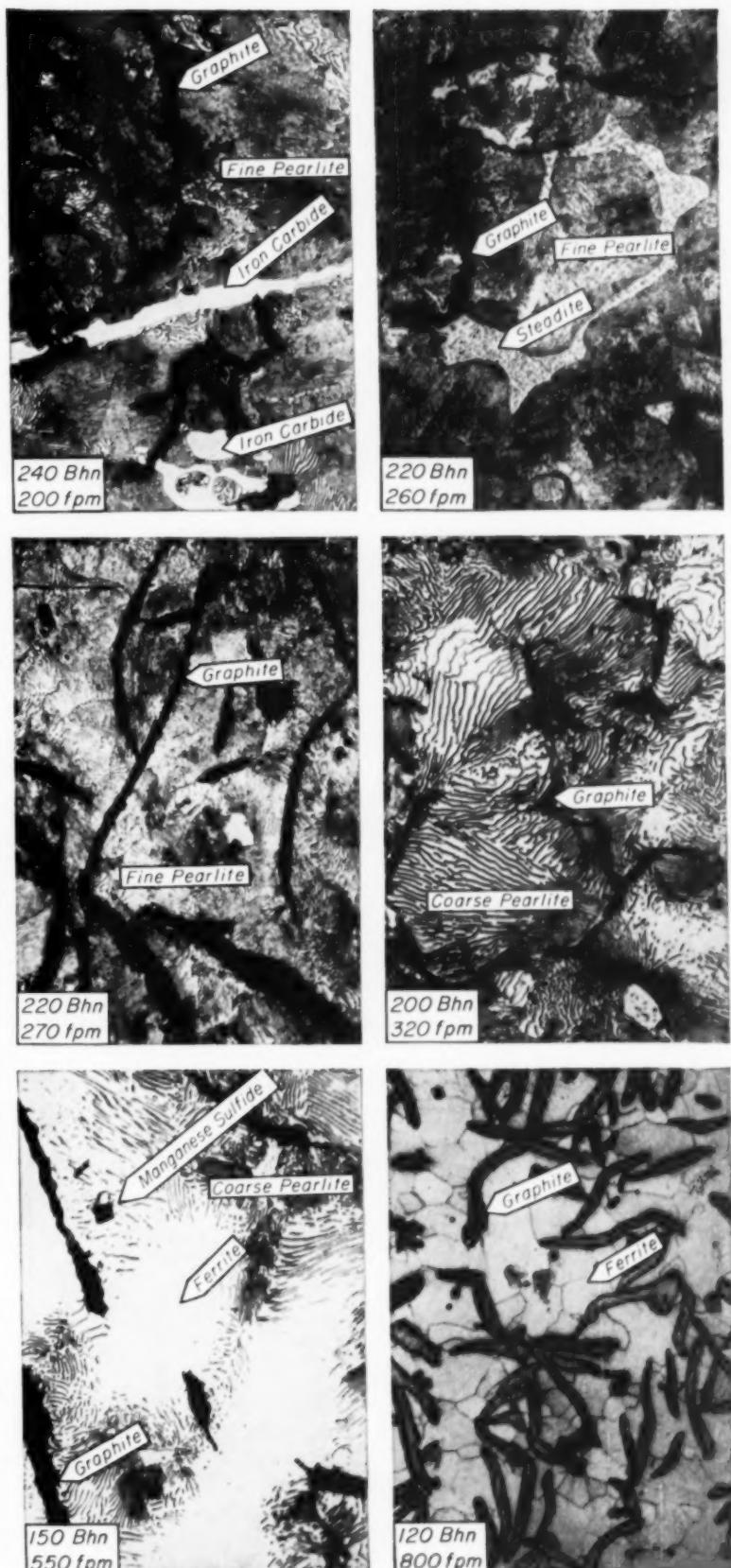
Malleable Iron and Nodular Iron have the same important microconstituents as gray iron and they influence machinability in the same way. The graphite in malleable and nodular irons is in rounded form, rather than as flakes. As in gray iron, however, the matrix structure of malleable and nodular iron controls tool life. The tool life increases with the percentage of ferrite, and decreases with increased percentage or fineness of pearlite.

Annealed Cast Irons. Most nodular irons and all malleable irons are an-

Fig. 11. Microstructures of Six Gray Cast Irons. Effect of structure on 60-min tool life (V_{60}) is indicated by the cutting speeds shown (in fpm), along with the Brinell hardness number, in the lower left corner of each photomicrograph. Percentages of microconstituents (neglecting graphite) in the six structures are approximately as follows:

Bhn	V_{60}	Microstructure
240	200	95% fine pearlite, 5% iron carbide
220	260	95% fine pearlite, 5% steadite
220	270	100% fine pearlite
200	320	100% coarse pearlite
150	550	50% coarse pearlite, 50% ferrite
120	800	100% ferrite

The V_{60} values above are for carbide tools. Curves of tool life in terms of metal removed and cutting time over a range of cutting speeds are shown in Fig. 12 for three types of gray iron.



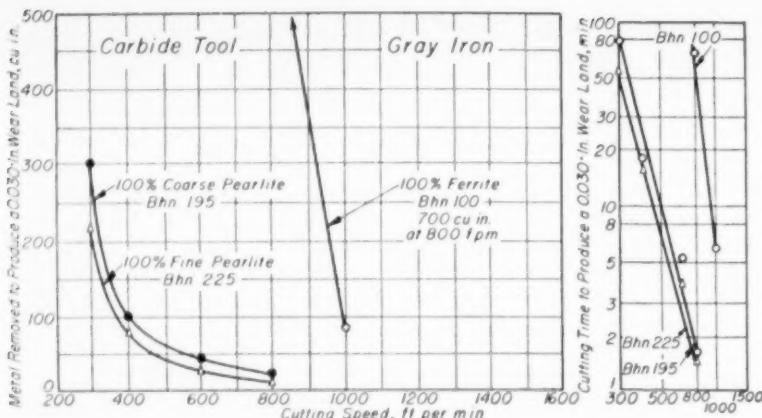


Fig. 12. Tool Life Curves: Metal Removed and Time Required to Produce a 0.030-In. Wear Land on a Carbide Tool versus Cutting Speed for Three Gray Cast Irons of Different Microstructure. Tool angles in degrees: back rake, 0; side rake, 6; side cutting edge angle, 0; end cutting edge angle, 6; relief, 6. Nose radius, 0.050 in.; feed, 0.010 ipr; depth of cut, 0.100 in.

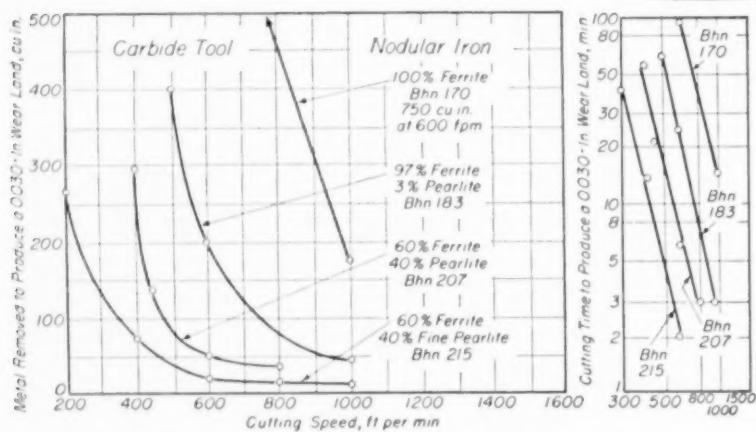


Fig. 13. Tool Life Curves: Metal Removed and Cutting Time to Produce a 0.030-In. Wear Land on a Carbide Tool versus Cutting Speed for Four Nodular Cast Irons. Tool angles and other conditions, same as Fig. 12

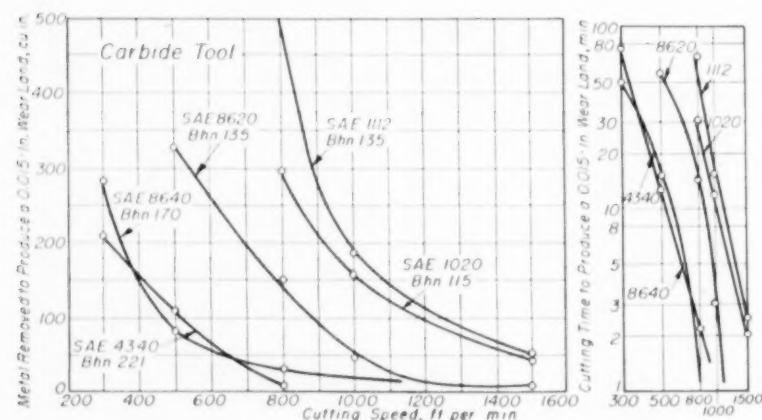


Fig. 14. Tool Life Curves: Metal Removed and Cutting Time to Produce a 0.030-In. Wear Land on a Carbide Tool versus Cutting Speed for Five Annealed Steels. Tool angles and other conditions, same as Fig. 12, except nose radius 0.040 in.

nealed before machining. If annealing is incomplete, excessive amounts of pearlite and even massive carbide may be present. Equivalent microstructures of annealed cast irons, regardless of composition, hardness or strength, indicate equivalent machinability, and this is actually observed. Tool life curves for typical gray irons are given in Fig. 12 and for nodular iron of various microstructures, in Fig. 13.

Steels. Tool life in the machining of steel is influenced by chemical composition, hardness, and microstructure. Medium-carbon alloy steels give nearly the same tool life when they have the same hardness and microstructure.

Tool life for steel is increased by: (1) large percentages of ferrite, (2) coarse pearlite as contrasted with fine pearlite, (3) fine spheroidized carbide as contrasted with massive carbide and (4) free-machining additives such as sulfur, lead, selenium and others. Network iron carbides, which may be present in annealed carburized parts, decrease tool life.

Typical tool life curves for five annealed alloy steels machined with carbide are shown in Fig. 14, and the same steels machined with high speed steel tools are shown in Fig. 15. The relative positions of these curves show the importance of composition on tool life and cutting speeds.

The tool life curves in Fig. 16 and 17 illustrate the relationship between heat treatment (and resulting hardness) and cutting speed. As shown in these curves, a single steel (8640) has a wide range of cutting speeds, depending on the heat treatment.

Various indices have been used to describe relative machinability. Simple indices are subject to error because they attempt to summarize a complex set of conditions in a single number. Some advantage can be found in using a speed number V_m , which is the cutting speed in feet per minute that will give 60-min tool life under given cutting conditions. Values of this speed number which indicate reasonable starting conditions for many machining operations are given in Table II. These data are actual test results (Ref 8 and 9) and specify the variables of microstructure, heat treatment and hardness for which they are valid.

Cutting Fluids

Cutting fluids are commonly applied to cutting tools to improve surface finish, dimensional accuracy or tool life. Their basic functions in accomplishing these improvements are:

- 1 To decrease the friction, welding or adhesion that occurs between chip and tool
- 2 To cool the tool and work piece by carrying heat away from the zone of cutting
- 3 To transport chips away from the cutting zone

While these functions are frequently operative at the same time, one or another may assume the role of major importance, depending on the particular operation.

As described earlier (under Mode of Tool Failure) wear occurs on the face and flank of a cutting tool by abrasion from the chip and work surfaces, respectively. The chip is forced against the tool face with very high pressure but still the surface of the chip will

touch the tool face only at the highest points on the two surfaces. The intimate engagement between these contacting points permits the establishment of minute welds which are continually being made and broken by the passage of chip and work, thus giving rise to a friction force on the tool, and progressive wear.

Figure 18 is a photomicrograph of a cross section through an actual chip-tool interface, relative motion between chip and tool having been suddenly arrested and the engaging surfaces maintained in their operating positions. This micrograph confirms the expected existence of a labyrinth of voids or capillaries between the contacting points on the interface, through which a cutting fluid (or its vapors) will therefore penetrate.

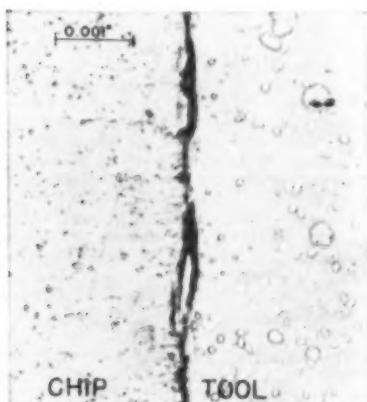


Fig. 18. Photomicrograph of a Cross Section through an Actual Chip and Tool Interface Immediately behind the Cutting Edge, Showing the Existence of Voids

Much experimental evidence has been accumulated (Ref 10) to indicate that an effective cutting fluid decreases friction and reduces wear by reacting chemically with the chip metal to form solid separating films of low shear strength materials. Such chemical reactions are possible because of the unique conditions of high local pressure and temperature at the contacting points, and a freshly formed metal surface.

The action of carbon tetrachloride may be considered to illustrate the principles involved, even though this material is of little commercial value as a cutting fluid because of its toxicity, volatility and cost. When carbon tetrachloride is used to cut steel, a small quantity of the fluid is drawn to the tool point by capillary forces and reacts with the chip under the extreme conditions obtaining locally. Iron chloride is formed which has a low shear strength and is not readily displaced from the surface on which it is produced. If the cutting speed is not too great, sufficient iron chloride may be formed to prevent the steel chip from welding to the tool face, and the cut will be produced without a built-up edge and with a minimum of heat.

Further confirmation of the chemical action theory of friction reduction in metal cutting is given by Table III, which shows that certain fluids may

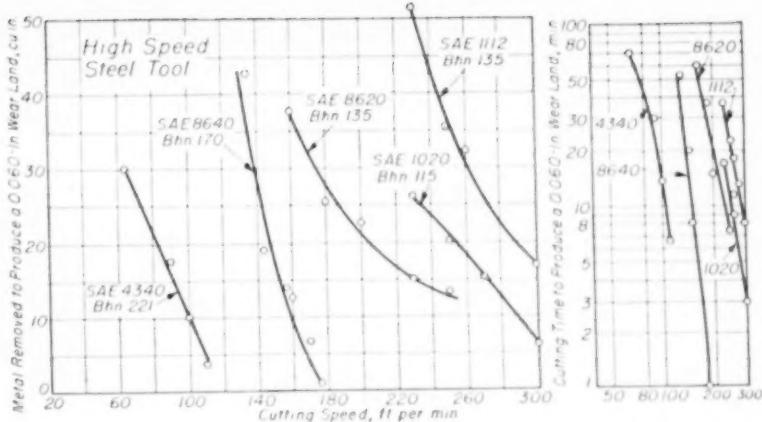


Fig. 15. Tool Life Curves: Metal Removed and Cutting Time to Produce a 0.060-in. Wear Land on a High Speed Steel Tool (18-4-1) versus Cutting Time to Produce a 0.060-in. Wear Land for Five Annealed Steels. Tool angles in degrees: back rake, 6; side rake, 15; side cutting edge angle, 0; end cutting edge angle, 5; relief, 5. Nose radius, 0.005 in.; feed, 0.009 ipr; depth of cut, 0.062 in.

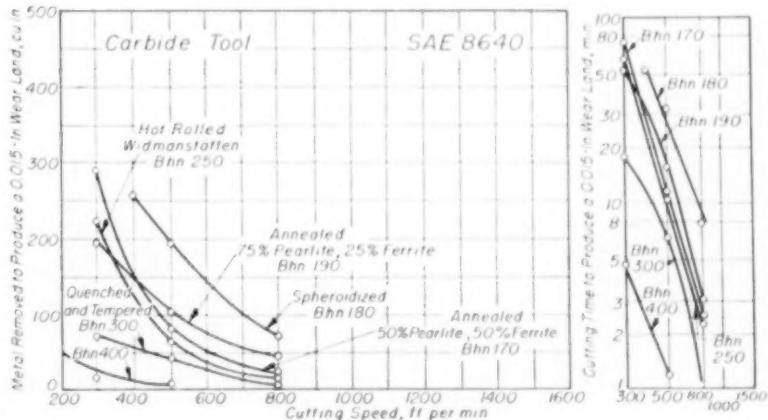


Fig. 16. Tool Life Curves: Metal Removed and Cutting Time to Produce a 0.030-in. Wear Land on a Carbide Tool versus Cutting Speed for Six Microstructures of 8640 Steels. Tool angles and other conditions, same as Fig. 14

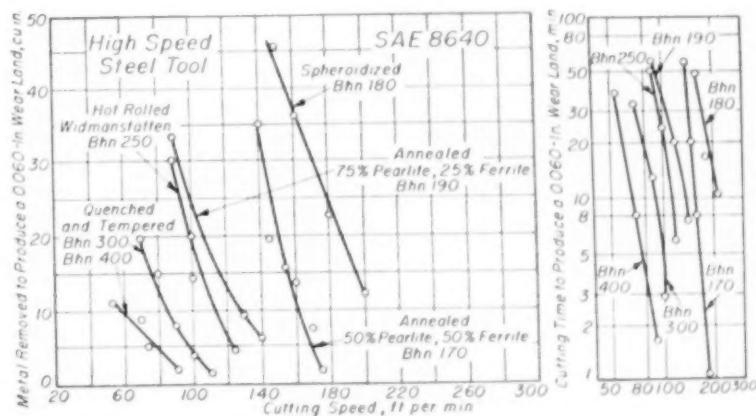


Fig. 17. Tool Life Curves: Metal Removed and Cutting Time to Produce a 0.060-in. Wear Land on a High Speed Steel Tool (18-4-1) versus Cutting Speed for Six Microstructures of 8640 Steels. Tool angles and other conditions, same as Fig. 15

Table II. Cutting Speed Numbers for Steel and Cast Iron^(a)

Alloy ^(b)	Condition or Heat Treatment ^(c)	Structure ^(d)	Bhn	Speed Number ^(e)	
				HS Steel ^(f)	Carbide ^(g)
Steels					
1112	Hot Rolled	10% P, 90% F	135	220	800
1020	Annealed	10% P, 90% F	115	150	550
9620	Annealed	50% P, 70% F	135	150	480
3140	Annealed	75% P, 30% F	190	75	280
3140	Q & T	Temp Mart	302	55	200
4140	Annealed	65% P, 35% F	180	60	330
4140	Annealed	90% P, 10% F	192	75	225
4140	Spher	Spher	166	125	560
4140	Q & T	Temp Mart	300	55	210
4340	Annealed	100% P	221	70	260
4340	Spher	Spher	206	80	375
4340	Q & T	Temp Mart	300	45	260
4340	Q & T	Temp Mart	400	30	225
4340	Q & T	Temp Mart	500	15	125
5140	Annealed	80% P, 20% F	192	85	240
8640	Annealed	50% P, 50% F	170	125	325
8640	Annealed	75% P, 25% F	190	90	280
8640	Spher	Spher	180	130	375
8640	Hot Rolled	W	250	85	310
8640	Q & T	Temp Mart	300	60	...
8640	Q & T	Temp Mart	400	40	150
52100	Spher	Spher	190	100	275
1345	Annealed	80% P, 20% F	207	80	290
4817-H	Annealed	W Spher	217	90	450
9262-II	Annealed	100% P ^(h)	255	60	150
14B45	Annealed	0% P, 40% F	167	150	295
94B17	Annealed	40% P, 60% F	167	150	540
80B40	Annealed	100% P	212	80	260
81B40	Annealed	95% P, 5% F	207	80	290
86B45	Annealed	95% P, 5% F	212	65	...
98B40	Annealed	100% P ^(h)	202	80	330
50B60	Annealed	100% P ^(h)	205	95	220
Cast 1020	Annealed	30% P, 70% F	122	160	400
Cast 1020	Normalized	30% P, 70% F	134	135	230
Cast 1040	Dbl Norm	70% P, 30% F	185	130	400
Cast 1040	Norm & Ann	60% P, 40% F	175	135	380
Cast 1040	Normalized	70% P, 30% F	190	120	325
Cast 1040	Norm & O Q	80% P, 20% F	225	80	310
Cast 1330	Normalized	60% P, 40% F	187	75	140
Cast 1330	Norm & Temp	60% P, 40% F ⁽ⁱ⁾	160	120	230
Cast 4130	Annealed	50% P, 50% F	175	95	260
Cast 4130	Norm & Spher	Spher	175	90	200
Cast 4340	Norm & Ann	85% P, 15% F	200	60	210
Cast 4340	Norm & Spher	Spher	210	95	290
Cast 4340	Q & T	Temp Mart	300	45	200
Cast 4340	Q & T	Temp Mart	400	35	180
Cast 8430	N & T 1200 F	Fine Spher	200	90	200
Cast 8430	N & T 1275 F	Fine Spher	180	110	240
Cast 8630	Normalized	70% P, 30% F	240	75	180
Cast 8630	Annealed	55% P, 45% F	175	120	290
Cast Irons					
Gray Iron	Annealed	100% F	100	...	800
Gray Iron	As-C Slow Cool	Coarse P	195	...	320
Gray Iron	As-C Fast Cool	Fine P	225	...	270
Gray Iron ^(j)	As-Cast	Acicular	262	...	170
Nodular 1	As-Cast	80% P, 20% F	265	...	220
Nodular 2	As-Cast	40% P, 60% F	215	...	320
Nodular 3	As-Cast	40% P, 60% F	207	...	390
Nodular 1	Annealed	30% P, 70% F	183	...	500
Nodular 3	Annealed	100% F	170	...	780

(a) Cutting speed number is the cutting speed in feet per minute which causes a given flank wear land on the tool in 60 min. Flank wear land on high speed steel tools was 0.060 in.; on carbide tools, 0.015 in. for cutting steel and 0.030 in. for cutting cast iron. All of the results are for turning operations. The depth of cut was 0.062 in. and feed was 0.009 ipr for high speed steel tools; for carbide tools, depth of cut was 0.100 in. and feed was 0.010 ipr. Data from Ref 8 and 9. (b) Carburizing steels (0.20% C) are usually received in the hot rolled condition; medium-carbon steels, either hot rolled or annealed.

(c) Abbreviations used in this table: Ann, annealed; As-C, as-cast; Dbl, double; F, ferrite; Mart, martensite; N or Norm, normalized; O, oil; P, pearlite; Q, quenched; Spher, spheroidized or spheroidite; T or Temp, tempered; W, Widmanstatten.

(d) 18-4-1 high speed steel. (e) General-purpose cast iron grade of carbide for cutting cast irons; general-purpose steel grade for steels. (f) Partly spheroidized. (g) Coarse pearlite. (h) Pearlite spheroidized. (i) High-alloy cast iron.

act selectively with respect to two different metals while others may be either effective or ineffective on both. In further tests, carbon tetrachloride was found to be effective on all metals tested except lead. Its ineffectiveness on lead might be expected from the fact that the lead chloride which is formed at the interface has a higher shear strength than the lead junctions which would be formed if the carbon tetrachloride had not been used. Hence the friction force at the interface was increased.

In the lower range of cutting speeds the friction-reducing effect of the cutting fluid is of greatest importance. At the higher speeds the cooling effect should predominate.

Cutting fluids in common use are of two classes: water-base and oil-base. The former are generally used in applications where cooling is of major importance; however, when formed as a chemical emulsion with suitable additives, they may also provide an effective reduction of friction. Oil-base fluids, usually with various additives, are generally used for the heavier, slow-speed operations or where considerable chip crowding occurs, as in internal broaching, gear cutting and threading. In such operations, friction reduction is of major importance.

Cutting fluids should preferably be applied to both the face and flank surfaces of a cutting tool, so as to surround the cutting region.

Production Planning

The object of planning a machining operation is to achieve optimum initial machining rates, which can subsequently be revised, either for least cost or greatest production.

Production Costs. An analysis of production costs will show the factors which can be varied to decrease the costs (Fig. 19).

The idle and loading costs represent the noncutting time of normal production. This time may be reduced if the proper tooling and proper incentive for the operator are at hand. The use of loading fixtures, automatic speed changing, centralized controls, rapid power traverse, prelocating of tools as in the turret of a turret lathe, and even automatic work handling, such as is used in many of the high-production automotive plants, will all reduce this idle and loading time. It is not unusual for the idle and loading time to occupy from 40 to 80% of the total machining time, and this time, per piece, is not affected by cutting speed.

The cutting cost represents the time that the tool is actually cutting. In job shops this usually represents a small proportion of the total time, whereas in high-production work, especially in automatic machines, the cutting time may represent a large proportion of the total time. To reduce the cutting time requires that the metal be removed at a faster rate, which in turn requires that more power be available or that the method of cutting be more efficient. Increasing the cutting speed will decrease the cutting cost, as shown in Fig. 19.

The tool changing cost increases rapidly as the cutting speed is increased. The cost covers the time for the operator to remove, replace, and reset the tool, and get the machine running

Table III. Influence of Cutting Fluid

Cutting Fluid	Appearance of Surface		Cutting Ratio		Cutting Force, lb	
	Al	1020	Al	1020	Al	1020
Acetic anhydride	Bad	Good	0.18	0.41	154	363
Turpentine	Good	Bad	0.35	0.25	78	493
Carbon tetrachloride	V. Good	V. Good	0.39	0.48	65	212
Benzene	V. Bad	V. Bad	0.13	0.22	182	535

Al, aluminum; 1020, 0.20% C steel; V, very

Table IV. Typical Values of n and $(\frac{1}{n} - 1)$

Tool Material	Work Material	n	$(\frac{1}{n} - 1)$
Carbon tool steel and high speed steel	Steel, soft	0.12	7.3
	Steel, hardened	0.15	5.7
	Cast iron	0.15	5.7
Sintered carbide	Steel, soft ^(a)	0.20	4
	Steel, hardened	0.25	3
	Cast iron	0.25	3

Anti-seizure types of cutting fluids decrease the value of n approximately 10% for steel. (a) For cutting speeds above 300 fpm

again. If the operator regrinds his own tools, this time should be included.

The tool grinding costs include depreciation of the original tool cost and the cost of labor, grinding wheels, and other equipment and supplies. These are computed as dollars per tool grind. As shown in Fig. 19, this cost may become excessive if cutting speeds are too high.

An analysis of costs for single point tools is as follows:

Costs Per Piece include:

1 Idle cost per piece = $K_1 \times$ Idle time per piece. Includes loading, unloading and tool approach

2 Cutting cost per piece = $K_2 \times$ Cutting time per piece =

$$K_2 \left(\frac{L\pi D}{12fV} \right)$$

3 Tool changing cost per piece = $K_3 \times$ Tool failures per piece \times Tool changing time

$$= K_3 \cdot \frac{\frac{1}{L\pi DV^n} - 1}{\frac{1}{12fC^n}} \times T_{CT}$$

4 Tool regrinding cost =

$K_4 \times$ Tool failures per piece =

$$K_4 \left(\frac{L\pi DV^n}{12fC^n} \right)^{\frac{1}{n} - 1}$$

where:

K_1 = direct labor rate + overhead rate, \$ per min. Includes operator and helper's labor, maintenance, power, depreciation, insurance

K_2 = tool cost per grind, includes original and regrinding costs, \$ per tool

L = length of cut, in.

D = diameter of cut, in.

V = cutting speed, fpm

f = feed per rev, in.

$VT^n = C$ is the equation of cutting speed and tool life

T = tool life, min

T_{CT} = tool changing time, min

These four quantities can be added graphically to obtain the total cost curve as shown in Fig. 19.

From this curve it is evident that for this example the minimum cost per piece will be obtained at a cutting speed of about 250 fpm.

Tool Life for Minimum Cost. Tool life varies inversely with cutting speed according to the equation $VT^n = C$, which plots a straight line on log-log paper and nearly a straight line from actual test data (Fig. 12). (V is cutting speed, T is tool life between resharpenings, n is the slope of the curve of cutting speed versus tool life and C is a constant equal to V when tool life is 1 min). The value of the exponent

n is fixed for a given combination of tool material and dimensions, cutting fluid and work material. Typical values of n are given in Table IV.

The equation for the middle curve of the right-hand chart in Fig. 12 is $VT^{n-1} = 900$. This relationship is needed to calculate preferred tool life for minimum cost and for maximum production rate. The preferred tool life for minimum production cost is:

$$T_{min_cost} = \left(\frac{1}{n} - 1 \right) R$$

where n is the exponent in the equation $VT^n = C$, and R is the ratio of cost of changing and regrinding the tool to the cost of labor and overhead. For the lathe operation represented by Fig. 12 the data necessary to find the desired tool life are:

Labor rate \$2 per hr = \$0.033 per min
Machine overhead \$3 per hr = \$0.050 per min

Tool changing time, $T_{CT} = 5$ min

Tool depreciation cost = \$0.95 per grind

Tool regrinding cost = \$0.85 per grind

Tool changing cost =

$$5 \times (0.033 + 0.050) = \$0.415$$

$$R = \frac{0.415 + 0.95 + 0.85}{0.033 + 0.050} = \frac{2.215}{0.083} = 26.7$$

The factor $(1/n - 1)$ in general may be taken from Table IV, but in this example is taken as $(1/0.27 - 1)$.

$$T = \left(\frac{1}{0.27} - 1 \right) 26.7 \\ = 2.7 \times 26.7 = 72 \text{ min}$$

and the corresponding cutting speed from Fig. 12 is about 320 fpm.

Maximum Production Rate. The tool life for maximum production rate is $(1/n - 1) T_{CT}$ where T_{CT} is the tool changing time in minutes, and includes loading time but no other idle time. If maximum rate of production is desired, with higher tool cost, the tool life is

$$T = \left(\frac{1}{n} - 1 \right) T_{CT} \\ = 2.7 \times 5 = 13.5 \text{ min}$$

and the corresponding cutting speed from Fig. 12 would be 490 fpm.

Nomographs have been prepared for

computation of tool life for minimum cost (Fig. 20) and for maximum production rate (Fig. 21).

Dimensions of Cut. As indicated by the data shown in Fig. 22, the dimensions of cut influence cutting speeds in two ways: (1) larger cuts, regardless of dimensions, usually remove more metal for the same tool life and (2) greater depth of cut is more effective in removing additional metal than greater feed, for the same tool life. These relationships conform to the equation $V_m f^{n-1} d^{m-n} = K$, where V_m is the cutting speed for 90-min tool life, f is feed and d is depth of cut. As shown by the larger exponent for f in the equation, deep cuts are better than heavy feeds. When depth of cut is doubled, speed is reduced 22% but metal removal is increased 56%. When feed is doubled, speed is reduced 34% and metal removal is increased only 31%.

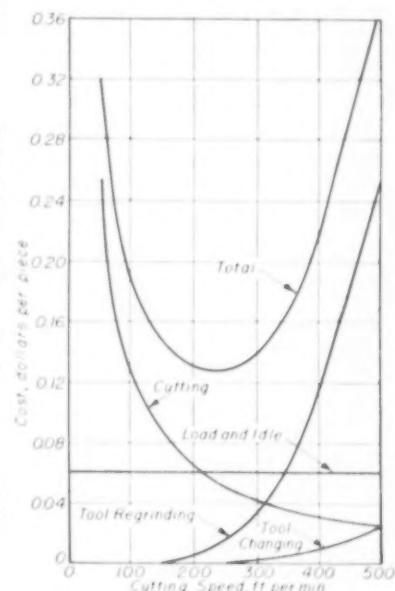


Fig. 19. Example of Variation of Machining Cost with Cutting Speed for One Set of Conditions

An increase of feed and depth of cut, together with a corresponding reduction of cutting speed, will increase tool life and decrease power consumption for the same rate of metal removal. The size and depth of cut are limited only by the forces on the tool, the power available, tool chatter, finish and inaccuracy of dimensions because of tool deflection under load.

Selection of Cutting Speed, for the previously computed optimum tool life, may be made by one of four methods,

Table V. Cutting Speed Conversion Factors

Ratio of T_1 or f_1 or d_1 to T_2 or f_2 or d_2	Cutting Speed Multipliers		
	$\left[\frac{T_1}{T_2} \right]^{1/n}$	$\left[\frac{f_1}{f_2} \right]^{-m}$	$\left[\frac{d_1}{d_2} \right]^{-m}$
0.25	0.85	0.43	0.66
0.5	0.92	0.66	0.81
1.5	1.05	1.27	1.13
2.0	1.09	1.52	1.23
4.0	1.18	2.39	1.52

depending on the data available.

In the first method, when no data are available, the cutting speed may be increased in successive trials until the tool life for the computed minimum cost is reached.

The second method can be used to convert a single available figure for cutting speed at a given tool life to a new cutting speed for the desired tool life. This method applies to both high speed steel and carbide tools. Data that will serve as an excellent starting point for turning operations are listed in Table II, in the section Work Metal and Tool Life, page 148.

The conversion of these data to the desired tool life involves the equation:

$$V_2 = V_1 \left[\frac{T_1}{T_2} \right]^{0.125} \left[\frac{f_1}{f_2} \right]^{n-0.1} \left[\frac{d_1}{d_2} \right]^{n-0.8}$$

where T_1 is 60-min tool life and T_2 is the desired tool life computed previously. To simplify the conversion to the second cutting condition, multiply the known cutting speed by the factors listed in Table V. This method lends itself to simultaneous conversion of several cutting conditions.

A third method of finding the cutting speed is to use the nomograph or alignment chart shown in Fig. 23. This is a graphical representation of the equations involved in the second method, for a limited range of steels. It is based on the equation

$$VT^{0.125} f^{0.1} d^{0.8} = K_{tm} K_{mc}$$

which expresses the relation between cutting speed, V , tool life, T , feed, f , depth, d , and the constants, K_{tm} for tool material and K_{mc} for metal cut. Cutting speed can be found readily from this chart when the other factors are known or assumed. The constant C in $VT^n = C$ may be read from Fig. 23 when tool life is taken as 1 min.

The fourth method of selecting cutting speed is based on tool life curves. Figure 12 is an example of such data. It is the simplest of all methods when feeds and speeds are to be the same as used in the existing data. However, cutting conditions used to obtain the data normally are different from the optimum conditions; therefore, the additional use of the second or third method will predict better initial cutting conditions.

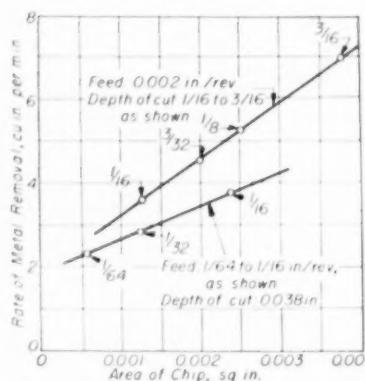


Fig. 22. Influence of Variable Feed and Variable Depth of Cut on Machining Rate for 90-Min Tool Life. Medium carbon steel cut with high speed steel tool (Ref 11)

The use of tool life curves for the prediction of machining facilities necessary to perform a given operation may be illustrated by an example. Consider a shaft of 3.200-in. diam, to be machined from 3.500-in. diam 8640 annealed bar stock of 170 Bhn. Assume

that the bar to be machined is 15 in. long, depth of cut is 0.150 in., feed per revolution is 0.010 in., as in the data. The tool is carbide. The suitable cutting speed can be read as 325 fpm from Table II on page 148.

Production rate can be computed in the following steps: 354 rpm; feed rate 3.54 ipm; machining time per shaft 4.2 min; floor-to-floor time per piece, assuming 0.5 min for loading and unloading, will be 4.7 min; and production rate will then be about 12 per hour.

Assume further that production requirements are 48 pieces per hr but only three machines are available for the operation. The increase in speed necessary to produce 48 pieces per hour on three machines will decrease tool life and increase tool costs. The loading time remains at 0.5 min. Computation shows that cutting speed must be increased to 480 fpm to meet the schedule with three machines. The effect of this increase on tool life can be read from the curve on Fig. 16. This shows a tool life of 15 min at 480 fpm as compared with 60 min at 325 fpm. Hence, if the work is done on three machines, the tooling costs will be increased 250%.

Tool life curves are shown in Fig. 12 to 17 of this article and additional data for other materials appear in Ref 8, 9, 12 and 13. These data are for 60-min tool life, a depth of cut of 0.062 in. and a feed of 0.009 ipr for high speed steel tools, but a depth of 0.100 in. and feed of 0.010 ipr for carbide tools.

General Recommendations. Chipping failure of carbide tools usually occurs because of insufficient rigidity of the work piece (inherent or otherwise) or insufficient strength of the cutting edge. Changes should be toward providing maximum rigidity to the work piece through a suitable work-holding fixture, and toward increasing the strength

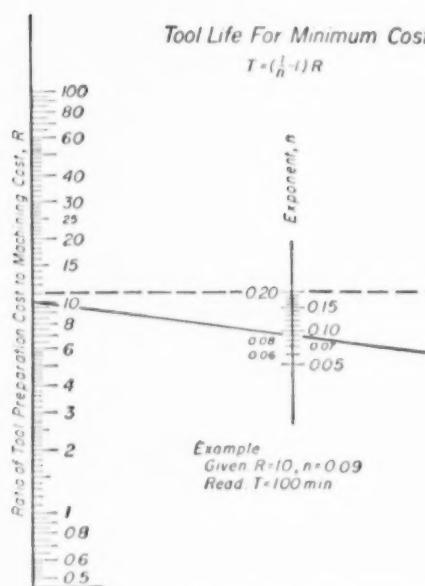


Fig. 20 (Above). Nomograph of Tool Life for Minimum Cost

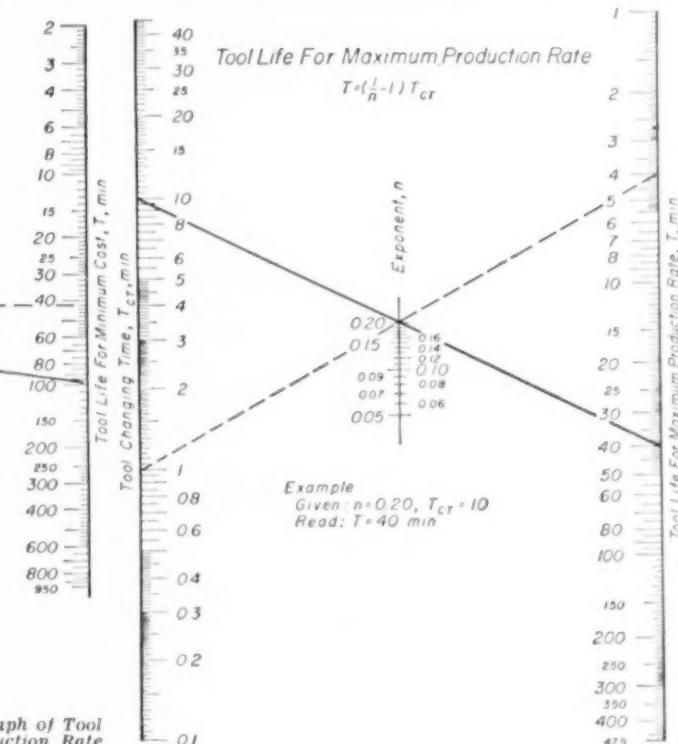


Fig. 21 (Right). Nomograph of Tool Life for Maximum Production Rate

of the cutting edge either by use of a more shock-resistant grade of carbide, decrease in rake angle, or by blunting the cutting edge at 45 deg with a hone to a width not more than about $\frac{1}{4}$ the feed.

Poor surface finish is caused by fragments of built-up edge which pass off with the machined surface during the formation of a type 3 chip; too small a nose radius; chatter; or too large a feed. The size of the built-up edge may be decreased by using an effective cutting fluid, increasing the cutting speed and increasing the true rake angle. Larger nose radii are generally beneficial to surface finish; however, they may cause chatter with a correspondingly rougher surface finish if the setup or work piece is not sufficiently rigid. Too large a feed will result in poor finish due to heavy feed lines in the work, or in extreme cases may initiate chatter due to excessive force on the work.

Chatter caused by a condition of unstable forces encourages chipping of the tool and poor surface finish. The tool support should be designed to prevent increase of chip thickness as the work or tool deflects under load. Smaller nose radius and smaller side cutting edge angle will reduce the separating force between work and tool. Greater rigidity in the tool, tool holder and work-holding fixture decreases the likelihood of chatter.

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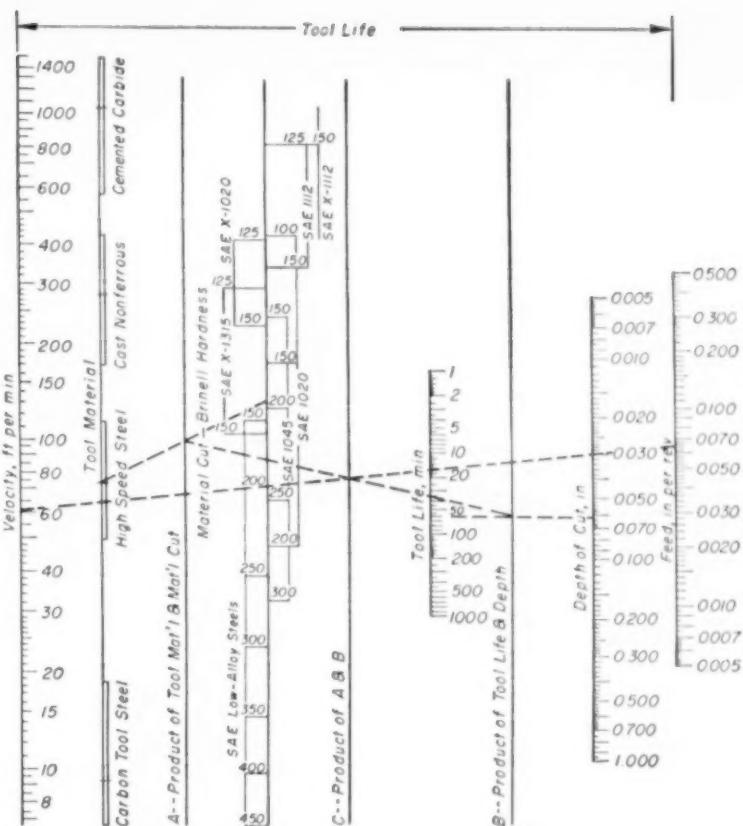


Fig. 23. Nomograph for the Calculation of Cutting Conditions for Carbon and Low-Alloy Steels

Machining, Joining and Finishing of Powder Metal Parts

By the ASM Committee on Powder Metallurgy

THE 1948 ASM METALS HANDBOOK gives a general review of powder metallurgy (pages 47 to 52) which emphasizes the primary operations of pressing and sintering, and includes data on the properties of metal powders and certain pressed and sintered test specimens.

The discussion here supplements the

1948 article by describing the machining, joining, finishing and other operations that are usually done by the user of powder metal parts, rather than the fabricator.

The information here is intended for those who may be considering the use of powder metal parts as well as those already concerned with them.

Machining practice depends greatly on the intended function of the part. Structural parts where porosity is either incidental or deliberately minimized can usually be machined with the same procedures employed for rolled or forged alloys; highly porous parts designed to provide self-lubricating bearing surfaces must be machined with special care to avoid smearing the metal and destroying the surface porosity. Usually, actual cutting of the bearing surface is avoided entirely;

Supplements the article on pages 47 to 52 of the 1948 ASM Metals Handbook

rather, the metal is pushed aside by ball-burnishing or coining. Coolants and lubricants are avoided because they may displace the lubricant in a porous bearing, sweat out and cause trouble in service. Instead, a low-pressure airblast can be used.

The recommendations which follow apply equally to porous bronze and porous iron (ASTM B202). Changes of the initial cutting condition will usually be necessary to achieve optimum cutting conditions.

Drilling. Speeds of 70 fpm (ft per min) for high speed steel drills and 200 fpm for carbide drills will produce satisfactory holes. Drills with a low right-hand helix angle, or sometimes a left-hand helix angle, will prevent the drill from digging in. The cutting edges should be "dubbed" or ground to reduce axial rake enough to prevent such digging.

Mechanical feeds should be used whenever possible and should be selected to achieve the desired finish if the drill is used for the final sizing operation, especially for the larger drills. The following feeds in inches per revolution (ipr) are satisfactory:

Drill Diam	Feed
$\frac{1}{8}$ to $\frac{1}{4}$ in.	0.002 ipr
$\frac{1}{4}$ to $\frac{1}{2}$	0.004
$\frac{1}{2}$ to $\frac{3}{4}$	0.006
$\frac{3}{4}$ to 1	0.010

Tapping. Conventional tap-drill charts should be followed to maintain about 65 to 75% of thread. Two-flute taps are recommended for diameters of $5/16$ in. and smaller; three-flute taps should be used for diameters from $5/16$ to $1\frac{1}{2}$ in. Spiral-pointed taps are desirable because they throw the chip out instead of driving it into the pores of the metal part.

Reaming. Left-hand helical reamers are recommended. The cutting edge surfaces should have a fine finish to minimize edge build-up, which results in oversize holes. The drill should leave a reaming allowance as follows:

Hole Diam	Allowance
$\frac{1}{4}$ in. or less	0.002 in.
$\frac{1}{4}$ to $\frac{1}{2}$	0.002 to 0.004
$\frac{1}{2}$ to 1	0.004 to 0.006

Reamers should be used in floating holders whenever possible and should be run at 25 to 50 fpm. Feeds are as follows:

Hole Diam	Feed
Up to $\frac{1}{4}$ in.	0.005 ipr
$\frac{1}{4}$ to $\frac{1}{2}$	0.007
$\frac{1}{2}$ to $\frac{3}{4}$	0.010

Turning and Boring. Frequently, a projection, a re-entrant angle or a large taper, not obtainable by pressing, can be machined, preferably with a carbide or diamond tool. Experimentation is generally needed to develop the optimum tool shape and feed. The depth of cut should be between 0.005 and 0.015 in. to prevent smearing the metal. After grinding the tool, all cutting faces should be carefully honed to provide keen, smooth cutting edges. The tools must be kept sharper than those used for machining wrought metals.

With high speed steel tools, cutting speeds are 90 to 110 fpm, and with carbide tools 175 to 350 fpm. Feeds are limited by the shape of the tool. For example, if a nose radius of $1/16$ in.

were used, a feed of 0.010 to 0.015 ipr would be suitable. If the nose radius is decreased to 0.010 in., the feed should be decreased to between 0.003 and 0.005 ipr to obtain a smooth, cleanly-cut surface. Figure 1 will serve as a starting point for design of carbide tools.

The above values for turning may be increased for roughing operations or when a porous surface is not required. Speeds of 500 fpm are not excessive with carbide tools and may be as high as the limits of the parts dictate. Feeds of 0.030 ipr may be used.

Milling. Carbide milling cutters are recommended. The conventional helical tooth cutter with axial rake on the teeth will shear the chips cleanly. For a short run, parts may be machined with the same cutters used on cast iron, bronze, and other alloys of low tensile strength. As in other machining operations, tools should be kept sharp. A corner bevel is preferred to a radius.

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and smaller corner radii are preferred to larger ones.

High speed steel cutters should be operated at about 70 fpm and carbide cutters at 250 to 300 fpm, for general-purpose work. Carbide cutters should be used whenever possible to maintain size and finish for a long period between grinds. If a wear land $1/64$ in.

wide appears on the back of the tooth, or if wear becomes visible on the cutting edges, the cutters should be replaced. Failure to change cutters will result in a condition that retards the passage of oil.

A feed of 0.010 to 0.015 in. per tooth is recommended for roughing work with carbide cutters. For finishing, feeds of 0.002 to 0.005 in. per tooth should be used.

Shaping. A carbide or high speed steel tool ground as shown in Fig. 1 may be used as a starting point for shaping or planing, at the top speeds available on most machines. On older machines the tool is not lifted auto-

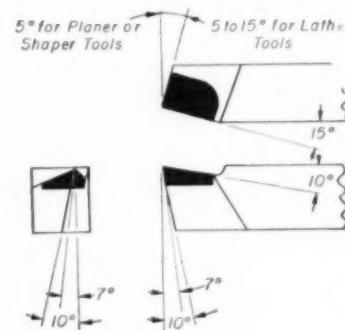


Fig. 1. Tool for Turning, Boring, Planing or Shaping of Powder Metal Parts

matically on the return stroke but the operator must lift the clapper box by hand or provide a means for doing so automatically, to prevent chipping the tool and thereby marring the finish. Since shaper and planer feeds are too coarse to provide the necessary finish on sintered parts, the end cutting edge angle of the tool shown in Fig. 1 may be changed from 5 deg to about 2 deg so the heel will barely clear the work and will remove its own feed marks.

Grinding and Lapping of porous parts is not recommended because abrasive particles may become embedded in the pores, dislodge in service and damage bearing surfaces. Infiltrated or plastic-impregnated parts may be cylindrical ground or centerless ground with the usual techniques, without special precautions.

Burnishing of bronze, brass or iron is recommended for fits of ± 0.0005 in. or less between bearing bores and shafts, after the bushing is assembled in the housing to insure trueness of the hole. No more than 0.002 in. per in. diam should be removed; the smallest

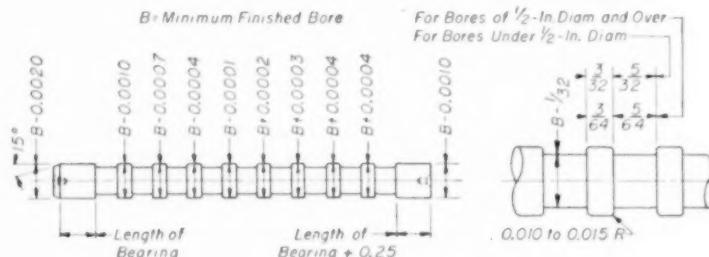


Fig. 2. Ball Broach for Burnishing Powder Metal Parts

Table I. Effect of Coining on Tensile Properties of Iron Compacts

Initial Density	Tensile Strength, psi		Elongation, %	
	Pressed & Sintered	Coinced at 55 tsi	Pressed & Sintered	Coinced at 55 tsi
6.6	23,000	48,000	6.8	1
6.8	26,800	52,000	7.0	1.8
7.0	30,500	53,500	7.0	2.6
7.2	34,000	55,000	8.2	3.4
7.3	36,500	57,500	10.5	3.8
7.4	38,000	57,000	9.5	4.8

From W. J. Doecker and H. T. Harrison, Proc Metal Powder Assoc, 1953. Data for compacts of electrolytic iron powder sintered at 2070 F for 45 min.

amount that can be cleaned up successfully is preferred because surface porosity is lost in proportion to the amount of material displaced by burnishing. The type of tool recommended for this operation is shown in Fig. 2.

Figure 3 shows a sapphire tool for burnishing holes $\frac{1}{2}$ -in. diam and smaller, in either a high-speed lathe or drill press. A drop of light lubricating oil is used and the work piece is pushed onto the rotating tool.

Sizing and Coining

Sizing produces parts to extremely close dimensional tolerances without primary concern for mechanical properties. The tools and presses may be those which produced the original compacts, and similar pressures are employed. Steel dies are satisfactory but carbide dies will produce many more pieces within tolerance. Bearings are frequently sized during assembly by inserting an arbor into the bore. A light oil film on the part will facilitate sizing, but any appreciable impregnation must be avoided because hydrostatic pressure built up in a die can explode tools and injure personnel.



Fig. 3. Tool for High-Speed Burnishing of Holes in Powder Metal Parts

Coining increases density and improves mechanical properties (Table I), and is also used to obtain contours of greater complexity than produced in the first pressing operation. As in sizing, the coining dies would be similar to the original pressing dies; compacting pressures, which could be as high as 200,000 psi, are limited by the strength of the tools, the capacity of the press, and the ductility of the metal. Tolerances obtainable by sizing also apply to coining, but, because of the higher pressures, tool wear and die maintenance are greater. If tolerances of 0.002 in. per in. or less are required, coining tools must be undersize to allow for elastic recovery of the part upon release of pressure.

Joining

Iron or bronze parts not economically producible in one piece can often be made as two pieces joined by brazing, or by projection or spot welding. Brazing is limited to parts of high den-

sity, finished by coining or infiltration. On parts of low or medium density, the brazing filler metal will infiltrate the part rather than filling the joint by capillary action.

Spot welding is restricted to pieces about 1/16 in. or less in thickness and having a small area. Projection welding is most useful for joining large areas. In projection welding, one or both of the mating pieces are pressed with a projection or boss of the type shown in Fig. 4.

The electrodes may also function as the assembly fixture. In general, the procedures are the same as for wrought alloys except that the currents required are lower. Weld time cycle, hold time cycle and current all increase with projection diameter and height.

Staking is a useful assembly method because most powder metal parts retain considerable malleability. Star, ring and knife staking tools similar to conventional tools can be used but the metal should be worked in compression rather than curled or displaced laterally.

Impregnation and Infiltration

Impregnation of sintered bronze or iron bearings with lubricating oil is generally done either by a "vacuum-pressure" method or by prolonged soaking in hot oil. Depending on the application, a wide variety of oils—silicone, anti-creep, low and high viscosity—may be specified. Bearings used as inserts in castings or moldings are normally specified dry and are oil-impregnated in assembly. To seal surface pores as a preparation for plating and other finishing, a porous part may also be impregnated with commercial resins—polyesters are the most popular.

Infiltration is one of the newer processes used to improve ferrous powder metal parts by filling the pores with molten copper, brass or bronze. Parts made of brass or bronze may be infiltrated with lead to obtain high density. Infiltrated parts exhibit full density and greatly improved mechanical properties. Machining and plating of infiltrated parts are routine because of the absence of porosity.

Heat Treating

Heat treating can increase the tensile strength and hardness of ferrous sintered parts at the expense of ductility. Ferrous parts can be case hardened, but gas carburizing should be used on porous parts. Liquid carburizing should be avoided because of corrosion following entrapment of salts. Infiltrated or full-density parts can be quenched and tempered conventionally, and surface hardened by carburizing, nitriding and cyaniding.

Surface Finishing

The simplest finishes (burnishing and scratch brushing) are frequently used on brass and nickel silver parts before lacquering for protection from oxidation. Iron parts can be economically finished either by steam treating, which both blackens and hardens the surface, or by an oxidation process in which the parts are heated in air to about 850 F and then quenched in an oil-water emulsion. Parts thus treated exhibit higher hardness and better resistance to rust and wear.

The chromizing treatment, which is a gas reaction process for iron powder metal parts, produces a silver gray finish which is hard and wear-resistant and has good resistance to corrosion in industrial atmospheres. (See page 706, 1948 Metals Handbook.)

Commercial plating finishes such as copper-nickel-chromium, cadmium, zinc, silver and gold have been successfully applied to both ferrous and non-ferrous parts. The pores must first be closed by coining, burnishing, buffing, carefully controlled shot peening or resin impregnation. Unless the pores are closed, the plating salts, pickling acids and alkaline cleaners are trapped and discolor the finish, cause internal corrosion and "flowering" of the plate. Prolonged rinsing, followed by drying or baking, is necessary to remove all traces of solution.

Infiltrated and high-density parts of all metals are easily plated using standard procedures, and can be hot tin-plated for surface protection. Low-density parts are not normally hot dipped because they would absorb large quantities of the liquid metal.

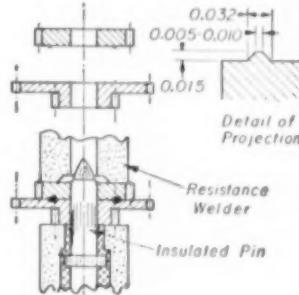


Fig. 4. Assembly Fixture and Details of Projection Welds on Powder Metal Parts

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Steel Melting

By the ASM Committee on Melting

THE TECHNOLOGY of liquid steel has advanced in many ways during the last decade. The most important of these advances are discussed here, with emphasis on the two largest tonnage processes—basic open hearth and electric—and two new techniques, vacuum melting and continuous casting of steel. Advances in Bessemer practice, particularly instrumentation, are dealt with more briefly, as are several significant developments in pit practice.

The Bessemer Process

The principal advances in Bessemer practice in the past decade have been in the direction of larger vessels of improved design, added instrumentation for operational control, and certain modifications in the method of blowing designed to improve the quality of the finished steel.

Converter Design. A definite trend is developing toward construction of larger converters. Where previously 30 tons was considered the maximum practicable size, new installations based on 40-ton vessels are now under contract. In one instance the shape of existing 25-ton vessels has been altered to accommodate a charge of 38 tons at normal bath depth. In Europe, converters of 50 to 60-ton capacity have been operated successfully, but these are basic-lined in contrast with the acid-lined converters used in this country. The limit of converter size has not been definitely established but appears to be restricted only by economic considerations and the extensive changes to supplementary facilities that would be required with larger units.

Control of the Blow. Control of the Bessemer blow traditionally has depended on the skill of the individual operator in his judgment of temperature, end-point, afterblow and other factors. Two devices have now been established as useful adjuncts to the blower's eye in detecting significant changes in the Bessemer flame. One of these, the spectroscope, measures flame radiation in a localized area at the base of the flame near the converter mouth. The approach of the end-point is shown by the flickering of certain characteristic, bright spectral lines or bands, which completely disappear when the end-point is reached.

The second accepted system for controlling the end-point is the photocell flame control or "electric eye". This apparatus includes a light-sensitive photronic cell positioned to pick up radiations from the converter flame, an amplifying system for multiplying the output of the light-sensitive cell, and an indicating and recording device.

In both these methods, the observer must have good color perception. Accurate control results in greater uniformity from blow to blow and improved quality of the finished steel.

Supplements the six articles on steel melting, pages 320 to 337 of the 1948 ASM Metals Handbook

Subdivisions	Page
The Bessemer Process	154
The Basic Open Hearth Process	154
Basic Electric Furnace Melting	155
Ingot and Pouring Practice	156
Continuous Casting of Steel	157
Vacuum and Atmosphere Melting	158

Reliable instrumental means for determining temperature in the converter are not yet developed in this country. In Europe, however, it is common practice to measure the temperature of Thomas (basic) converter steel with portable immersion thermocouples inserted into the vessel after turnaround.

Control of Nitrogen and Phosphorus. One of the major factors contributing to the decline of the acid Bessemer process has been the adverse influence of relatively high contents of nitrogen and phosphorus in the steel. This has led to studies of new techniques for eliminating these elements while preserving the many advantages of pneumatic refining processes.

As nitrogen finds its way into the steel by absorption from the air blast, two possible means of holding it to a minimum are indicated: (1) decreasing the proportion of nitrogen in the air blast by adding high-purity oxygen, and (2) surface blowing, in which a large part of the blast impinges on the surface of the metal, and does not actually pass through it. High phosphorus probably requires a fundamental change in practice from acid to basic and a slag sufficiently basic to hold the phosphorus. This in turn would require a change from acid (siliceous) to basic refractories (magnesite or dolomite) for the vessel lining. Adequate control of both nitrogen and phosphorus will probably be attained through utilization of high-purity oxygen for refining molten iron in basic-lined converters.

The Basic Open Hearth Process

Although the fundamental principles of metallurgy and operation of the basic open hearth furnace have remained unchanged since the early Siemens-Martin furnaces were built, a more thorough understanding of these principles by operating personnel has increased the speed and efficiency of open hearth production during recent years. Prior to the second World War, there was a constant effort to improve design, refractory life, and fuel efficiency. Since 1940 furnace operators have been called on to produce larger tonnages from existing equipment. This increased production was achieved through the use of deeper baths and by certain necessary changes in practice. Postwar construction in new furnaces and plants, however, has brought a more efficient design of furnace with a long shallow bath, rapid charging and maximum fuel input.

Furnace Construction. The rapid increase in the steelmaking capacity of the country in the past few years has been accompanied by an even greater rise in the average capacity of furnaces. While the total annual capacity of open hearth furnaces at 109 million net tons on January 1, 1954, was nearly 30% higher than in 1945, the average capacity of these furnaces per heat had been increased 37%, to approximately 160 tons. Despite the many new furnaces built since the war, the total number of open hearths had been reduced to 934 at the beginning of 1954, from 990 in 1945.

Most furnaces built today range in size from 200 to 300 tons and tap into one ladle; the bath is approximately 30 in. deep; hearth areas are from 800 to 1100 sq ft. A number of furnaces are now operating with 300 to 550-ton capacity and tap into two ladles through a bifurcated spout.

Some of the most significant advances in furnace construction have been directed toward improving combustion efficiency, and in the judicious use of basic brick in both ports and bulkheads, as well as in the furnace walls. Silica brick continues to be the best for roof construction. Bottoms are now either fully or partially rammed with high-magnesia refractory mixes. Such material has shortened the time required to install new hearths by as much as two weeks. Quick repairs to bottoms and slopes are made with rammed and gun-mix materials.

Raw Materials Handling and Mechanical Aids. Some bulk refractories and deoxidizers are now packaged in paper bags of convenient size. Bricks and bags are palletized and handled by lift trucks. Sizable bath and ladle additions are brought to the furnace by small trucks or other mechanized equipment. Some plants are equipped with elevators to bring stock or refractories up to the floor level.

A dolomite gun is used to make the back wall. Banks are made up, and spill cleaned from the floor, with the aid of diesel-driven buggies and bulldozers. Checkers are blown regularly with air or steam or washed down with special solutions. Flue dust is removed by a vacuum system.

Electric buggies and small cranes are being used on the pouring platform in some shops to assist in handling the heavy caps for rimmed and "bottletop" steel.

Types of Charge. The following types of charge are now being used in open hearth practice:

- 1 Conventional: raw limestone, scrap and hot metal
- 2 High metal ore charge: raw limestone, ore, scrap and hot metal
- 3 Blown metal: raw limestone, scrap and blown metal
- 4 Duplex: burnt lime and liquid metal
- 5 Cold charge: burnt lime, scrap and cold iron

Charging. In shops where ore is charged, a low-silicon iron is preferred in order to keep both the required limestone and the resulting slag volume low. A large flush is most desirable to obtain maximum effect of the available lime. For best results, the oxides charged must be of optimum size, low in silica and combined moisture. Where good natural ores are not obtainable, a good grade of sinter is used.

Open hearth design necessarily re-

stricts operations to door-by-door front charging of scrap, in contrast to top charging in electric furnaces. To speed the charging, scrap is prepared so as to increase its unit weight by shearing, torch cutting or baling. Charging boxes are larger than formerly, with capacities between 40 and 60 cu ft. Special switches and lifts for individual furnaces are in use to accelerate delivery of the charge to furnaces. Furnace doors are larger.

Stepped-up scrap charging schedules reduce temperature loss and hasten melting. Melting is accelerated in some shops by a higher heat input through oxygen enrichment of the combustion air. Combination burners equipped for gas, oil or tar and oxygen are used in many shops. Flame temperature is further increased by raising the temperature of regenerated air.

Furnace Instrumentation and Control. Automatic control by furnace instrumentation increases production and efficiency with lower cost in fuel and refractories. The following are commonly used: automatic fuel-air ratio control, automatic reversals based on checker temperature or time, roof temperature control, and furnace pressure control.

With the help of such instruments, the furnace can be operated at a slight positive pressure, thus preventing infiltration of cold air at the wicket holes and doors, and minimizing heat losses from the furnace proper. The instrument panel is equipped with a bath temperature dial and chart in addition to the usual meter equipment for indicating and recording the flow of oil, gas, oxygen, steam and water.

New techniques have been developed recently for measuring air temperature in the uptakes, and in analyzing furnace and flue gases. These, together with studies of pressure, flow and velocity of gases and their relation to throat area, have done much to maximize production and minimize consumption of fuel and refractories.

Metallurgical Control Factors. To produce a low-sulfur steel with normal fluctuations in hot metal and scrap, a high lime-silica ratio must be maintained. On charges high in hot metal, the amount of free lime depends on whether a good flush is obtained. The flush naturally rids the charge of a large quantity of silica before the lime reaction, thus making more lime available for removing sulfur and phosphorus, with a minimum of limestone charged.

Slag control is now made more effective by spectrographic checking of the lime-silica ratio. While there probably have been no recent advancements in slag control as such, the reactions are much better understood, and this knowledge is more widely used.

Heats are worked down in carbon by ore or oxygen or both. Oxygen is used also to help increase the temperature at various stages of the operation, in bringing up the lime, shaping up the slag and bringing the heat to proper tapping temperature. Oxygen is introduced into the bath through a "lance" (a 3-in. pipe, 20 ft long) through the wicket hole in one or more of the doors. Outlets with pressure gages and safety valves are set up at each furnace. In some shops, more than one lance of larger diameter is used. To prevent blocking the charging tracks, some in-

stallations use water-cooled jets inserted through the back wall.

Both the carbometer and combustion methods are used for preliminary carbon determinations. Sulfur analysis by the combustion method saves considerable time. Residual alloying elements are determined by the spectrograph, often of the direct-reading type.

The temperature of the bath is checked by immersion pyrometers during the process, as an aid to removal of sulfur and phosphorus, and in control of decarburization and deoxidation. The principal use of the immersion pyrometer, however, is to establish an optimum tapping temperature for the various grades, and to duplicate that temperature from heat to heat.

When the heat is ready to tap, the hole is dug out and a "bazooka" jet

have been found to give better surface on certain applications.

Statistical Analysis of operating variables has come into more extensive use for maintaining both metallurgical and production control of surface quality, interior cleanliness, mechanical properties and other variables.

Basic Electric Furnace Melting

During the last decade, larger furnaces, top charging, and maximum rate of energy input have combined to increase unit production and make the electric furnace an important factor in the manufacture of plain carbon steels, thus extending its field beyond that of special alloy and stainless steels. Other significant improvements in design such as induction stirring and automatic power factor control speed the process, increase efficiency, and improve quality.

Perhaps the most outstanding development has been the use of gaseous oxygen in melting stainless as well as carbon and normal alloy steels. Noteworthy also are the advances in controlling hydrogen. Although the discussion here refers primarily to basic melting, many of the remarks on design apply equally well to acid furnaces.

Furnace Design and Construction. In 1930, electric furnace builders began to design furnaces so they could be charged from the top by removing the roof, thus introducing the entire charge at one time from a large drop-bottom bucket. It was not until 1950 that furnaces of 20-ft shell diameter or larger were top-charged. During the second World War a number of large door-charge furnaces were installed, of which only a few were equipped with transformer capacities up to 17,000 kva. Some of these have since been converted to top charge, and provided with transformers of larger capacity. Top charging is now common on large new units having transformer capacities up to 35,000 kva.

It appears that the limiting size has not yet been reached. Two furnaces with 22-ft diam shells were installed in 1952, and two 24½-ft units (nominal holding capacity, 180 tons) are under construction in 1954.

Several of the larger high-powered units use 24-in. graphite electrodes, with the rotating type of electrode control and the familiar winch. In repositioning electrodes in holders, remote-controlled clamps, operated from the floor, can now eliminate the undesirable manual work on top of the furnace.

Induction stirring of the bath is a noteworthy development, which started in Sweden in 1936 and was first applied commercially in 1947 on a 15-ton furnace. Another was installed in 1948, followed by four more in Sweden. In the United States, the first unit has now been in operation for more than a year on a 20-ft furnace, and a second of similar size is under construction.

Electrodynamic force stirs the bath, through a device best described as a section of the stator of a large polyphase motor. It combines a magnetic yoke with two coils connected to form a two-phase winding with two electrical poles. When mounted under the furnace it forms, with the metal bath, what amounts to an induction motor, in which the moving magnetic field penetrates the nonmagnetic furnace bottom plate and refractory lining into

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tapper is placed in the tap hole. This directed explosive charge breaks through about 14 in. of tap hole material to open the heat. Those operators using the jet tapper report faster taps, hotter heats, and straighter tap holes with no ridge.

Ladle and Pouring Practice. Several advances have been made in the handling of open hearth steel in the pit. The use of "bottle-top" molds, elliptical ladles and power stoppers, as discussed under *Ingots and Pouring Practice*, below, are examples.

In the pouring of rimmed steel, shot aluminum and sodium fluoride additions to the molds are helpful in controlling the rimming action. Silicon carbide is often used in the ladle in place of aluminum, for rimmed and mechanically capped steels. Nitrogen compounds are being added to increase the yield strength of sheets, tinplate and pipe.

Many plants are set up for the cooling, cleaning and conditioning of all molds. Molds for wide strip mill slabs are being made wider, thinner, and higher, because thinner ingots show less segregation. Such ingots require more edgework and thus produce a sound edge on the rolled slab. Some plants are pouring rimmed ingots as high as 90 in. Mechanically capped steel is poured to 95 in. Fluted molds

the bath. The low-frequency current is one cycle per second or less. When power is supplied to the coils by a two-phase a-c generator, current is induced in the molten metal, resulting in a mechanical force which causes the metal to flow along the bottom in the direction of the moving field, then up along the lining and back over the surface. By reversing the current in one of the coils, the direction of travel of the magnetic field is reversed, and thus the stirring is reversed.

The induction stirrer provides a suitable method of mixing the characteristically inactive bath in the later stages of the operation.

Furnace Control. Automatic power factor control is now in use on the newer furnaces. The heating capacity of a furnace varies directly with the current input up to a certain point, beyond which additional input reduces the useful energy and increases the kva demand. The optimum power factor is between 0.75 and 0.80, varying somewhat with each furnace. The control system is designed to hold the energy input at this point, and thus to keep the electrical efficiency at a maximum.

Melting Practice. A most important development in electric furnace melting practice is the use of oxygen in the manufacture of carbon and normal alloy steels, but its greatest value is for stainless steels. It accelerates operation, and to some extent decreases power consumption and increases the life of furnace linings. Oxygen-manufacturing systems of sufficient capacity to maintain a steady flow at suitable pressure have been installed in most plants.

Oxygen is introduced into the bath through a "lance", a $\frac{1}{2}$ to 1-in. iron pipe, attached by hose to the main supply line. The hose and all fittings must conform to rules governing the safe use of oxygen, and the lance must be free from any grease or dirt. The lance is placed through the furnace door opening with its end through the slag but not into the metal. Thus, the oxygen is made to impinge on the metal at the slag-metal interface.

Oxygen Treatment of Carbon and Normal Alloy Steels. An active carbon boil in the oxidizing period is usually necessary to reduce the sulfur, eliminate gases and produce clean steel. To obtain these results, enough carbon is added in the charge to assure an active boil, allowing the carbon to fall to the desired point. The carbon may be added in pig iron, anthracite, petroleum coke or other carbonaceous materials, preferably low in sulfur. In addition, sufficient lime is added in the charge or during melting to form a basic slag.

The oxidizing period starts with the melting of the charge and ends only when the heat is slagged off or, in single slag practice, when completely melted and ready to be shaped up for tapping. Practices vary in the use of gaseous oxygen. Some operators prefer to use it without the aid of other oxidizing agents, such as ore; less lime is then required to maintain a basic slag, since no acid oxides are being introduced from ore. On the other hand, with a high-carbon bath, decarburization with ore is fast so that possible improvement with oxygen is small. Furthermore, the iron value obtained from ore may compensate for the disadvantage of larger slag volume.

Thus, when ore or mill scale is used in the charge, less gaseous oxygen is required. Oxygen is sometimes convenient to melt fringe scrap around the edges and to raise the temperature of the bath.

Oxygen Treatment of Stainless Steel. Before gaseous oxygen came into general use, the conventional method of producing stainless steel was from a virgin scrap melt—that is, a charge of virtually plain-carbon steel scrap. Problems involved with revert stainless scrap in the charge were quite serious; one of them was the difficulty in obtaining and holding low carbon contents. Practices using excessive amounts of ore or mill scale in the charge for carbon reduction in the presence of high chromium achieved reasonable success, but all raw materials had to be selected with extreme care and melting procedure had to be very closely controlled. In the production of 0.08% max C, it was usually not practical to have much revert stainless scrap in the charge.

With gaseous oxygen large amounts of revert scrap can be used in the charge and stainless grades of less than

the oxidizing operation will contain a substantial amount of the oxides of chromium, manganese and iron. To recover these elements the slag is treated with reducing agents, usually ferro silicon, or ferro chromium silicon. Aluminum also may be used, either alone or in combination with the other deoxidizers. The excess slag formed during reducing is partially or completely removed, after which a second reducing slag is formed with lime and crushed silicon to protect the bath while the heat is being finished. Every precaution is taken to avoid carbon pick-up.

In the melting of 0.03% max C stainless steel, stainless scrap is seldom used in the charge. It is difficult to lower carbon below 0.03% with a high-chromium charge, and the recovery of chromium from the slag is extremely difficult after the very high degree of oxidation necessary.

Control of Hydrogen in Stainless Steel. During melting, stainless steels may absorb hydrogen, leading to what is known as bleeding or gaseous ingots. Gas may be absorbed during the reducing or finishing period of the heat, and can be observed by box samples taken from the furnace. Hydrogen may come from moisture in the charge materials, leaks in the furnace cooling system, or from high humidity in the atmosphere.

Both argon gas and dry air are effective for purging hydrogen from the bath. Argon is introduced through an iron pipe lance held close to the bottom of the bath, and is bubbled through the bath until the gaseous condition has disappeared, as indicated by periodic box sampling of the bath. Dry air having a dew point of -25°C (-14°F) gives comparable results when introduced in similar manner.

Pouring Practice. As in the open hearth, one of the most important developments in pouring practice is the power stopper, discussed below.

Ingots and Pouring Practice

Ladle Practice. The conventional stopper rigging on bottom-pour ladles, even on the very large ones, is simply a mechanical slide carrying a goose-neck, to which the stopper rod is attached. The slide is operated by a simple lever in the hands of the steel pouerer. Obviously such control on large ladles is laborious and for that reason alone can be subject to considerable variation. For this and other reasons, power-driven devices for operating the stopper and controlling the pouring of steel from bottom-pour ladles have found favor both in open hearth and basic electric practice.

The best known power device now in use, called the "autopour", consists essentially of a hydraulic cylinder which can be quickly attached to the ladle after the heat has been tapped and when it is ready to be poured into molds. The piston rod of this cylinder engages the stopper slide so as to impart an up-and-down motion to it, and the cylinder itself is actuated by two hydraulic lines from a motor-pump unit carried in the cab of the ladle crane. The steel pouerer operates the mechanism from his usual station on the pouring platform, either by a push-button control suspended from the crane cab, or by a small control lever

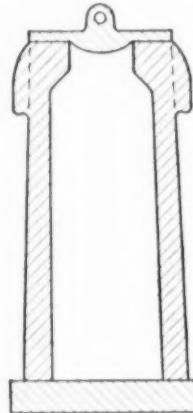


Fig. 1. Bottle-Top Mold

0.03% C can be produced. It has long been recognized that to decarburize a bath containing a high percentage of chromium, an extremely high temperature is required if high chromium is to be maintained at the low carbon level. Oxygen is an easy means of producing that high temperature. The essential relations among carbon, chromium and temperature have been developed (D. C. Hiltz, Proc Elec Furnace Conf, AIME, 1949).

The lance used for introducing oxygen into a stainless bath is usually protected with either a refractory covering, or it is water cooled, to conserve the pipe and to assure an uninterrupted flow of oxygen for an extended period.

Minor variations in practice which have not been precisely evaluated are the use of ore or mill scale in the charge and the starting of the oxygen blow either before or after melting is complete.

In order to insure best recovery of chromium, sufficient lime must be added to form a strongly basic slag. The power is usually turned off and the electrodes raised when the oxygen blow is started. The slag formed during

operating a valve at the base of the cylinder.

Because of the increase in size of individual ladles in some open hearth plants, a ladle of elliptical shape has permitted a shallower construction, thus reducing the ferrostatic head without decreasing the necessary ladle volume. It is interesting that many of the original ladles, of much smaller volume, used in the crucible practice of earlier years, were also of elliptical shape—for a different reason, however, that of fitting them into the narrow ladle carriages which were in vogue at that time.

Ingot Practice. In the pouring of semi-killed basic open hearth steel, "bottle-top" molds have come into use. As the name indicates, the mold has the big end down, with the top closed except for a short open neck, resembling the neck of a bottle, and designed to carry a metal cap (Fig. 1). The steel is partially deoxidized with aluminum or silicon carbide in the ladle, and aluminum shot is added in the molds to produce a rising steel. After the ingot has been poured, a heavy cap is placed over the opening in the top of the mold, and the rising steel then freezes against this top, thus minimizing segregation and shrink cavity.

Considerable work has been done toward improving hot top practice on killed steels. New exothermic and non-carbonaceous covering materials have been devised to assist feeding of the conventional type of brick or brick-lined hot top. In addition, methods have been developed for keeping the metal in the top portion of the ingot entirely molten during the feeding period by means of either an electric arc or a gas torch. Either of these methods can increase the yield and the soundness of ingot tops. When the arc is used, it is common practice not to use a refractory top. When a gas torch is used, a refractory top contains the liquid reservoir.

Continuous Casting of Steel

The continuous casting of large quantities of steel into relatively small "billets" has attracted steel makers for many years because it would eliminate the expensive blooming or cogging equipment involved in breaking down large ingots. Also inherent in the method is the improvement of the yield of good billets by eliminating the top discard necessary with conventional ingots, and the scaling and crop losses associated with an additional hot working operation.

Continuous casting of nonferrous metals is conventional practice, as described in the aluminum, copper and magnesium sections of the 1948 Handbook. Technical problems with ferrous alloys are greater because of the higher temperatures and the lower heat conductivity of steel. For these reasons, the continuous casting of steel is still in the development stage although several machines are now being built for commercial production.

The earliest work is often credited to Sir Henry Bessemer, who is reputed to have cast iron between moving rolls as early as 1858. The voluminous patent literature reveals two basic methods of operating: first, with the mold moving with the metal, such as split molds on an endless chain or rolls moving in the

direction of pour; and, second, with the metal moving through the mold. The latter system, in which the mold is referred to as "fixed", has been the subject of the most recent engineering effort. Most systems involve continuous operation, provided a continuous source of molten metal can be maintained.

Equipment. As shown in Fig. 2, the fixed-mold machines have the same basic elements: a source of molten metal, which may be a furnace or a ladle, delivering large quantities of steel at controlled temperature and rate to a tundish which regulates and distributes the molten stream to the mold, which is a bottomless water-cooled shell, either stationary or oscillating.

The casting emerging from the mold can be further cooled by air and water sprays before it passes through the withdrawing rolls to the cutting device.

Operation. In a typical continuous casting machine, the metal reservoir can be an induction furnace, but an insulated, heated ladle is preferred. The metal is held and poured within a narrow temperature range determined by the limits of nozzle freezing on the low side and by refractory damage and casting breakouts on the high side. Side-poured or bottom-poured tundishes are of simple design and can be equipped for automatic control of flow rate. A bottom-poured tundish helps prevent passage of slag to the mold,

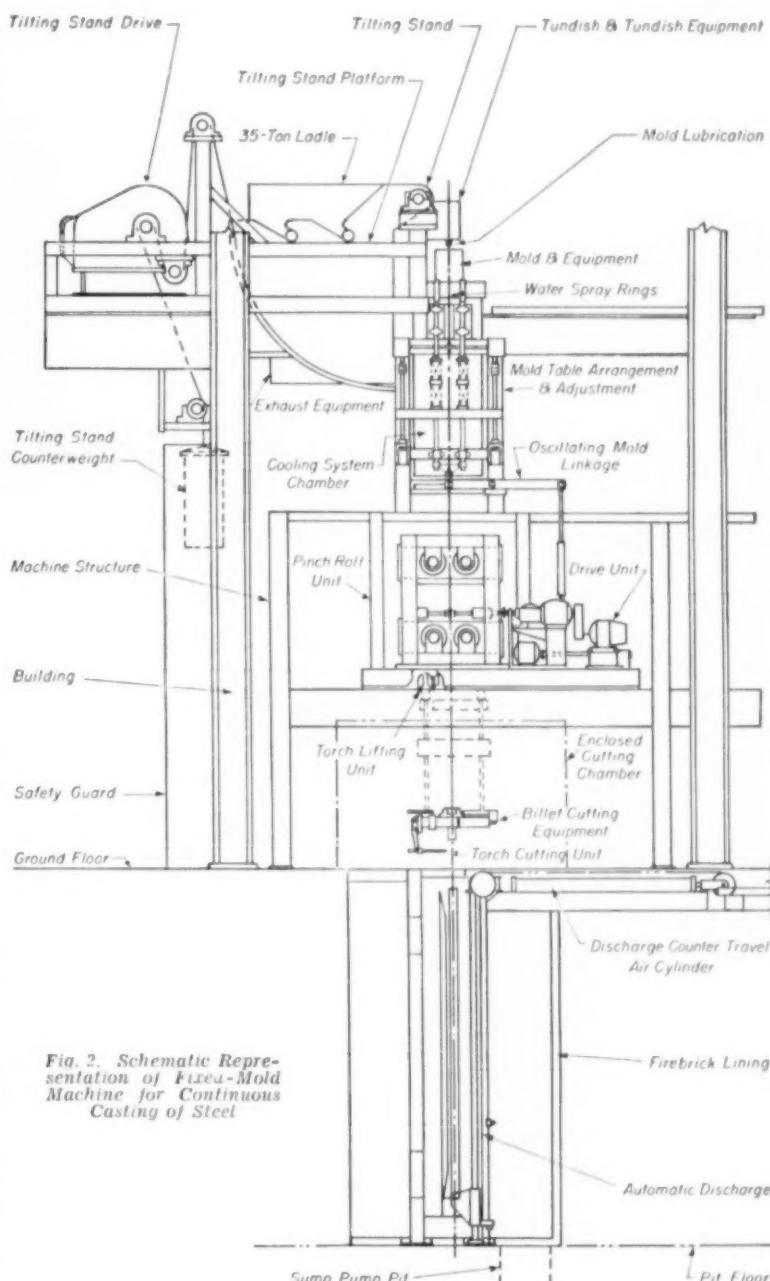


Fig. 2. Schematic Representation of Fixed-Mold Machine for Continuous Casting of Steel

but nozzle design is a limiting factor. Fused zirconia has worked well in this location.

Molten metal in the tundish and mold is protected from oxidation by a prepared atmosphere, obtained by burning a gas such as propane. The molten metal passes to the mold, which is generally made of copper for effective water cooling, with the inside surface chromium plated for wear resistance. In the Ross-Jungmans machine, the short (24-in.) mold is reciprocated by lowering for about $\frac{1}{4}$ in. at a rate synchronized with the speed of the withdrawing rolls and then snapping back to its original level by a spring and cam arrangement. Stationary molds are generally longer than the Ross-Jungmans design.

To start the pour, a dummy bar of conforming shape is positioned in the mold and held by the withdrawing rolls. The initial freezing takes place in the upper few inches of the mold forming a solid shell which shrinks away from the water cooled mold. Aided by mold lubrication, the casting moves steadily out of the mold at a rate determined by the speed of the pinch rolls which both support and withdraw the casting. Between the mold and the pinch rolls, water and air sprays complete the cooling required for solidification. Below the rolls, the casting is cut with a torch; a rapid and sure cutoff method is essential in continuous operation. It is obvious that the center must be solid before cutting, as the system from the mold down could be drained of molten metal were the center not entirely frozen. Casting rates vary from 5 to 20 tons per hr, depending on size and composition, and this rate can probably be increased by running two or more sections simultaneously in the same machine.

Product. Sections cast may be round, square, oval or rectangular. Although the size limitations have not been determined, square sizes from 2 by 2 in. to 12 by 12 in. have been cast, as well as slabs of 3 by 15-in. cross section. A wide variety of compositions in stainless steel, alloy steel, tool steel and carbon steel have been produced experimentally, all as killed steels. Successful operations have been reported on rimmed steel also. Grain size is somewhat finer than in regular ingots, and the surface obtained by proper operation requires no more conditioning than rolled billets.

Application. The direct economic advantage is increase in yield; as the billet or slab yield is over 95% of the molten metal, the gain is considerable. When blooming equipment is inadequate, the continuous casting machine would usually cost less than a modern blooming mill to produce sizes which can be continuously cast. Thus, while the larger integrated producer may be interested only in the increased yield, the smaller producer may find continuous casting an economical substitute for blooming equipment.

Vacuum and Atmosphere Melting

The control of pressure and composition of the gas over a melt permits deoxidation with carbon or hydrogen to give gaseous deoxidation products, and thus avoids inclusions originating in

the deoxidation process. Through the removal and exclusion of nitrogen, nitrides and carbonitrides may be eliminated from the microstructure of many steels and high-temperature alloys; and the prevention of oxidation losses permits very close control of composition-sensitive alloys. The improvements in physical and mechanical properties of some steels which result from such treatment are creating a demand for vacuum melting capacity in the United States. Production is still limited to $\frac{1}{4}$ and $\frac{1}{2}$ -ton operations, but units for melting more than 1 ton are planned.

Vacuum furnaces have been heated by arc, resistance, gas and induction methods, but only the latter has been used on any sizable scale for steels. The high-frequency induction unit operates independently of pressure, and size of the unit is not limited by structural supports. It also minimizes the refractory problems, while allowing

picked up by the bath, and the softening temperature is lower than for an electrically fused magnesite. The use of a magnesia lining in vacuum does, however, introduce a problem not encountered in open melting: At low pressures, liquid iron reduces MgO , to form magnesium vapor and dissolved oxygen.

Vacuum melting has often been employed simply as a carefully controlled remelting operation for very pure materials but it is more generally useful when a refining stage is incorporated. The principal refining action is the removal of oxygen, nitrogen and hydrogen, and of carbon when very low carbon is desired, as in some stainless steels. The elimination of nitrogen and hydrogen involves only a simple application of vacuum, since the nitrides and hydrides have low dissociation pressure, and the gases may be pumped off until their concentration reaches

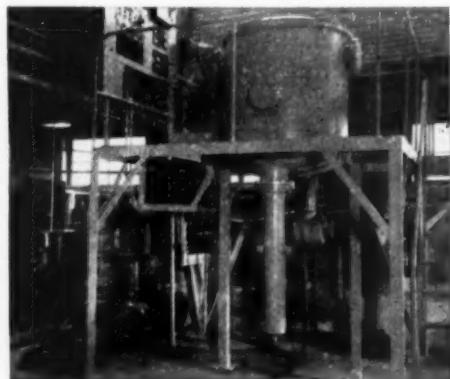
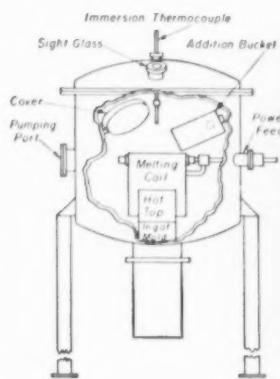


Fig. 3. Stationary Tank-Type Furnace for Vacuum Melting of Steel

melting temperatures up to 3800 F, and can be used with a cold vacuum tank.

For these reasons, the vacuum melting furnace for steel is of the high-frequency induction type, enclosed in a tank which is evacuated by a suitable pumping system and in which are incorporated vacuum seals through which the mechanical and electrical operation of the melting unit is accomplished. An early form of furnace, illustrated on page 333 of the 1948 Handbook, consisted of a vacuum tank containing an induction coil and crucible which were fixed within it and poured by tilting the whole tank. With the necessity for operation at much lower pressure and with increasingly larger melts, the use of a coil and crucible assembly which tilts within a stationary tank has become much more common. Figure 3 shows such a stationary tank-type furnace with its electrical and pumping systems. An advanced form of such a furnace (U. S. Patent 2,625,719) incorporates vacuum locks to permit charging of raw materials and discharging of ingots without exposing the melting crucible to the atmosphere (see Metal Progress for Sept and Oct, 1953).

The electrical frequency depends on the size of the unit, as in open furnaces, 10,000, 3,000, and 960 cycles being used over the size range of 30 lb to 1 ton. Basic linings or crucibles have been more common in vacuum melting. Although the acid hearth has better thermal and physical properties, silicon is

equilibrium. Ferrous metals cannot be deoxidized in this manner because the dissociation pressure of iron oxide is much too low. Deoxidation reactions which result in gaseous products may be used, particularly the reactions of carbon and hydrogen with oxygen.

Deoxidation with carbon is also very important in the control of carbon content of steels, since there may be a marked reduction in carbon content by the deoxidation reaction and by reaction with the lining. Another control problem is created by the volatility of certain alloying elements such as manganese, aluminum and chromium, which may cause high losses if the additions are made under high vacuum. These losses are minimized by the presence of an inert gas during addition.

When the steel is deoxidized and alloyed properly, a very clean and satisfactory product is obtained, even in certain steels that are notoriously dirty when manufactured by conventional methods, and in other steels for special uses in which higher cleanliness is required than acceptable under present standards. Of course, as in ordinary operations, exogenous inclusions must not be introduced from the furnace, nozzle or hot top refractories, during the tapping operation. The problems of the ingot which involve heat transfer and solidification mechanism are essentially independent of the pressure variable and hence similar to those of open practice.

Selection of Methods for Nondestructive Inspection

By the ASM Committee on Nondestructive Inspection

THE 1948 Metals Handbook describes seven methods of nondestructive inspection. This article compares the methods and deals with the selection of one or more methods for specific purposes.

In selecting a nondestructive test, the goal should be to select the method or combination of methods which provides the lowest cost inspection per unit and simultaneously evaluates reliably the necessary quality characteristics of the units involved. This is the ultimate criterion for selecting the most suitable methods and devices.

The physical principle of a test directly determines its applicability to a particular testing problem. Greatest emphasis should always be placed on technical applicability of a method, as indicated by an understanding of its physical principle, rather than on cost or convenience. The least expensive or most convenient test is not always the best. Confidence in the technical integrity of the method and the test operator is more important than low cost and extreme simplicity of procedure and equipment.

Table I shows typical "quality characteristics" of metals or metal products which can be evaluated nondestructively under favorable circumstances. These are the characteristics (either properties or defects) which contribute to or detract from satisfactory performance in service. Table I does not explicitly recognize a multitude of conditions observable by ordinary visual examination, although this is the most common method of nondestructive inspection. Table I is limited to those qualities most frequently and successfully evaluated in routine, production inspection. Excluded are qualities requiring tests so delicate or complicated that laboratory personnel or surroundings are needed.

Selection is further narrowed by the factors listed in Table II. Considered separately and collectively, these factors may either define the special applicability of a test or indicate a limited or complete nonapplicability. Further details such as metallurgical history or a drawing or photograph of the metal product are usually available. In addition, such factors as inspector training, the quantity of items to be tested, cost of test equipment and its operation, as well as time consumed in testing, should be considered.

Table III lists the available nondestructive tests in accordance with differences in testing principles. Only well evaluated methods are included. Brief descriptions follow.

Supplements the Nondestructive Inspection Section of the 1948 ASM Metals Handbook, pages 141 to 158

Penetrating Radiation

Radiography. Details of this widely used method are available from many sources. The 1948 Handbook treats the basic principles on pages 141 to 145. Penetrating radiation used in radiography is limited to beta rays (high speed electrons), gamma rays, X-rays, and (recently) neutrons from portable sources. Alpha radiation has such a short penetrating range that it is usu-

Subdivisions	Page
Penetrating Radiation	159
Sonic and Ultrasonic	
Methods	159
Penetrant and Pressure	159
Magnetic and Electrical	160
Optical Methods	160
Thermal Methods	160
Chemical Methods	161
Examples	161
Evaluation of Soundness of	
Arc, Gas and Thermit	
Welds in Steel	161
Detection of Cold Shuts in	
Cast Bronze Bushings	162
Nondestructive Inspection of	
Heat-Resisting Metals	162
Determination of Soundness	
in Aircraft Turbine Disks	162
Sorting Mixed Lots of Steel	163

ally impractical for industrial use. During the past few years, radio-isotopes suitable for gamma radiography have become available; detailed information on availability can be had from the Isotopes Div., AEC, Oak Ridge, Tenn.

Gaging with penetrating radiation is finding wide use for evaluating the total thickness of objects, thickness of thin coatings or deposits such as paint or electroplate, exploring or automatic scanning for discontinuities or gross inclusions in test objects, for chemical or structural evaluation by absorption or diffraction effects, and locating or gaging the heights of liquids or solids in closed vessels.

The requirements for gaging are: selection of a suitable source of penetrating radiation such as beta or gamma radio-isotopes, a suitable radiation detector which may be an ionization chamber, geiger counter tube, scintillation or crystal counter, and electrical equipment for indicating, evaluating or recording the radiation received.

Sonic and Ultrasonic Methods

The use of mechanical vibrations for nondestructive inspection logically divides into two fundamental classes. First, the generation of external mechanical vibrations ranging from audible frequencies up to 25 million cycles per sec, which are coupled to the part under test, with the part itself becom-

ing simply a medium for transmitting the sonic or ultrasonic waves.

The second class of mechanical vibration test requires that the entire test object vibrate as a whole when freely suspended and struck a single blow with a hammer. Resonant or natural vibrations occur which are characteristic of the material, its shape, method of fabrication, processing, and particularly the presence of gross defects. The damping or decay rate of these natural vibrations is also characteristic of physical and chemical properties of the material and can be used in inspection processes.

Ultrasonic applications of this principle employ the pulsed echo, resonance, through-transmission, immersion and other less familiar techniques. Wide industrial use has been made of ultrasonic methods for detecting and locating discontinuities or inclusions, evaluation of metal structure, and the measurement of thickness of objects from one side only.

Damping. The natural vibrations of a part, as when struck by a single hammer blow, are utilized as a means of nondestructive inspection. The decay of the vibrations can be measured by ear or by simple electronic timers and is widely used as a qualitative inspection method. Gross defects in castings may often be detected by the rapid decay of vibrations giving the characteristic dead sound after being struck with a hammer. By using vibration pickup microphones and elaborate electronic amplifiers and filter networks, highly accurate sorting gages can be devised for production line inspection.

Penetrant and Pressure

Liquid Penetrant Inspection refers to the entry of a liquid into surface defects and the detection of this liquid when it seeps from these defects. By making the penetrant fluorescent to ultraviolet light or by the addition of a suitable coloring agent, this seepage is readily detectable. Frequently seepage of the penetrant from fine defects is assisted by moderate heating of the part or is made more apparent by the application of a developer, which may be an absorbing, or a color-contrasting coating, such as chalk.

Gas Penetrant. Electrical halogen detectors, or simplified mass spectrometers and other devices, have made it possible to assemble large pieces of equipment vacuum tight. Specifications may be written indicating the tolerance range for gas leakage. Frequently liquid or gas penetrants are used to determine the necessity for impregnation of aluminum or magnesium sand castings for aircraft where gas or liquid seepage would be detrimental. Many simple techniques have also been used to detect gross leakage of a gas pressure differential; the soap solution is best known.

Pressure Differential. Pressure testing, as the name implies, requires that a differential fluid pressure be applied between two surfaces of a part. The fluid may be liquid or gas and for evaluating mechanical properties detailed specifications are usually prescribed for the type of service intended or to meet certain proof load tests. The reader is referred to boiler or pressure vessel codes and specifications for details.

Magnetic and Electrical Testing Instruments

Instruments for nondestructive inspection using magnetic or electrical principles have recently shown a marked increase. Early instruments were not widely used because of a lack of recognition of the interferences which occur and too little information on techniques for reducing or eliminating these interferences.

Table I. Typical Quality Characteristics Appraisable by Nondestructive Tests

A Soundness	(e) Porosity
1 Flaws at or within $\frac{1}{8}$ in. of the surface	(f) Inadequate penetration
(a) Cracks or tears	(g) Incomplete fusion
(b) Shrinkage cavities	(h) Flakes or bursts
(c) Misruns	(i) Laminations or cold shuts
(d) Inclusions	B Mechanical Properties
(e) Porosity	1 Hardness
(f) Undercuts	2 Miscellaneous structure-sensitive or strain-sensitive properties, and sorting
(g) Inadequate penetration	C Chemical Properties
(h) Incomplete fusion	1 Carbon content
(i) Flakes or bursts	2 Miscellaneous analysis and sorting
(j) Folds, laps or seams	D Dimensions
(k) Laminations or cold shuts	1 Thickness
(l) Blisters, scabs or pits	2 Location or position of hidden components
(m) Lack of bond	E Surface Roughness
2 Subsurface flaws	F Metallurgical Structure
(a) Cracks or tears	
(b) Shrinkage cavities	
(c) Misruns	
(d) Inclusions	

Magnetic Leakage. Magnetic lines of flux which deviate from the normal path due to the presence of defects in a part can be detected by a probe coil, magnetic particles, or other sensitive detectors. Variations in introducing the magnetic flux and in the design and use of the probe coil depend on the shape of the part being tested. In general the accuracy and sensitivity of the location of defects by the use of an external coil depend on many factors which require good technical knowledge and specialized coil design. Internal cracks in gun barrels have been successfully detected by using the magnetic leakage principle.

In magnetic particle methods, a magnetic field is induced in the part to be tested by the application of an electric current through the part or through a central conductor inserted through a hole in the part, or by means of a solenoid or coil. Any discontinuity at or near the surface of the part will interrupt the magnetic flux induced in the part and a leakage field will be formed at the surface in the vicinity of the defect. Any magnetic particles applied in the vicinity of this leakage field will be attracted, forming a visible indication which, properly interpreted, indicates some of the characteristics of the defect. The part is subsequently demagnetized. Further details are given on pages 145 to 149 in the 1948 Handbook.

Core Loss. The transformer action or variations on the transformer effect probably account for the majority of test instruments in this general field. In core loss methods the part is frequently used as the core. The magnetic effects analyzed in ferromagnetic material are usually confined to the eddy current and hysteresis loss effects.

Many variations of instruments based on measurements of core loss are available. One of the most widely used is

described in the 1948 ASM Handbook, pages 153 to 155.

Eddy Currents. This magnetic effect is listed separately as it is frequently useful for testing nonferromagnetic materials. The effect is essentially the same as a pure resistance to electric current, and defects, errors in analysis and other factors which affect the electrical resistance can be detected by magnetic eddy current analysis.

D-C Potential Drop. Although this test finds little use in industry, current

Tribo-Electric Effects. Static or electric charges generated by friction are used to distinguish between dissimilar metals. The effect must be analyzed empirically. A dry powder method has wide application on ceramics and enameling for detection of fine cracks or other flaws.

Optical Methods

Visual inspection is the examination by eye with or without magnification aids up to $10\times$.

Photo-electric. A natural extension of visual inspection is the use of photo-cell pickup. Under limited conditions photo-electric sorting can be combined with many other basic inspection methods. Production inspection of transparent objects using photo-electric sorting has been used, for example, checking double reflection of automotive safety glass.

Spectroscopic. Use of the portable spectroscope is mentioned on page 163. In experienced hands, analysis by visual observation of spectra can be semi-quantitative, which is important in separating low-alloy compositions from carbon steels containing the same element in small residual amounts.

Thermal Methods

Thermo-electric. This effect is commonly used for temperature indication by joining two dissimilar metals into a thermocouple. A new sorting instrument utilizes this principle.

Temperature-Sensitive Material. This method covers the broad field of heat flow distortion by the presence of defects or inclusions. Many methods have been proposed for detecting this

Table II. Typical Factors in Selecting Nondestructive Tests

A Type of Material	2 Up to 20 in. 3 Greater than 20 in.
1 Ferromagnetic alloy	
2 Nonmagnetic light alloy	
3 Nonmagnetic heavy alloy	
4 Nonconducting coating on metal base	
5 Nonmagnetic metal coating on ferromagnetic metal base	
B Fabrication Method	
1 Cast	
2 Wrought	
3 Powder metallurgy	
4 Joined	
(a) Welded	
(1) Fusion welded	
(2) Forge welded	
(3) Resistance welded	
(4) Brazed	
(b) Soldered	
5 Electroplated or coated by other surface deposition technique	
C Thickness of Material	
1 Thin films	
D Shape of Piece	
1 Flat surfaces	
2 Simple curved surfaces	
3 Complex geometry	
4 Pipe, tubing and containers	
E Surface Condition	
1 As fabricated	
2 Coated with scale	
3 Machined or ground	
4 Shot or sand blasted	
5 Buffed or brushed	
F Processing Treatments	
1 Carburized	
2 Nitrided	
3 Induction hardened	
4 Shot peened, pressure rolled, etc	
5 Special metal, surface diffusion or penetration coating processes	

may be readily detected by d-c potential probes.

Magnetic Attraction. The principal use of magnetic attraction as a non-destructive test method is for the measurement of nonmagnetic coatings on magnetic objects or vice versa. A prior calibration is usually required for the particular coating being measured. Instruments of this type are widely used in the laboratory and for production control tests. Beta-ray reflection gages are being used increasingly because of their speed and accuracy in production operations as discussed under gaging.

distortion by low-melting waxes, very sensitive contact thermocouple or electric resistance probes, visual and even photo-electric devices. Practically, the method is handicapped by lack of sensitivity and the sluggish response of heat flow measuring devices. Extensive experiments to detect lack of bond between electroplated bearing metal and base metal have given results inadequate for an inspection method. The method has some merit for special applications involving thin sections and poor heat conduction; for example, checking bonding of stainless cladding on steel strip.

Emissivity. A modification of the heat flow distortion inspection method takes advantage of the additional factor of emissivity. Metal objects, particularly large objects such as annealed furnace muffle sections, often visually reveal gross defects beneath the surface by differences in emissivity. Visual examination of the part at a bright red heat, while in an enclosure free from external light, may show gross defects such as shrinkage, gas pockets and hot tears by color differences (emissivity variation) due to heat flow distortion or differences in heat radiation.

Chemical Methods

Macro-Etching. The technique of revealing density, uniformity of structure, flow patterns, inclusions, laps and other surface defects, by chemical removal of the outer layers of test objects, is common. Etching solutions and techniques are adequately covered in the 1948 Handbook.

Chemical Spot Tests are widely used as a laboratory control for many plated, specially coated, or oxide film layers. Anodized coatings on aluminum are usually covered in specifications requiring chemical spot tests for thickness. Coatings or bulk material can be identified by simple spot tests. The results of chemical spot tests are qualitative only, and wide application is found in scrap metal segregation.

Large industrial organizations are finding that metal salvage operations are facilitated and made more profitable by an efficiently organized analytical and segregation program. Items 7B, 7C, and 5C form the basis of fast scrap and salvage analysis operations.

Spark Tests (Steels). The 1948 Handbook, pages 397 to 399, covers this subject in detail.

Examples

Generalizations about the selection and application of nondestructive tests are of doubtful value because any actual problem is a specific one. Tables I and II define the quality and selection factors which can be used to define and classify the problem. Table III lists the common nondestructive test methods according to their basic principles.

The plan of the remainder of this article is to discuss specific examples and the application of selected non-destructive inspection methods. Naturally, there are many local conditions regarding availability of skilled technicians, manpower, costs and the basis for requiring that a test be made,

which cannot be brought into the following examples.

When several competitive equipments are available, each should be demonstrated under anticipated shop operating conditions so that a fuller appreciation of simplicity, convenience, and cost of the proposed testing problem can be gained. Prototype specimens

the nondestructive tests should be synchronized with the operations that may initiate welding defects. Inspection before and during welding will reduce labor cost by detecting conditions which lead to defects as early in the production process as is possible, which often permits correction rather than rejection. Nondestructive tests are uniquely suited to such quality control.

Selection of nondestructive methods for unsoundness that may reduce weld strength depends on the type of steel and the shape of the piece.

Except for weldments of thin-walled tubular members, the most generally applicable nondestructive tests are visual examination, radiography, dye or fluorescent penetrant tests. For ferromagnetic welds, magnetic leakage techniques are also applicable. Although expensive in initial equipment costs, and too slow to be compatible with high production rates, radiography employing photographic image detection is the most complete and searching single inspection method. Radiography is therefore excellent for establishing qualified procedures and personnel and for the spot checking of finished items or portions of welds. Its slowness and expense, however, make it inapplicable to 100% inspection, except for special uses—for example, where failure would mean loss of life or great cost of equipment replacement. Also, for detecting cracks, radiography should be supplemented by visual examination and, for ferritic welds, by magnetic particle techniques. Both of the latter types of examination are less costly and more rapid than radiography.

In addition, magnetic particle tests are more reliable than radiography for detecting surface cracks in welds. For nonmagnetic welds in steel, not inspectable by magnetic methods, the dye and fluorescent penetrant methods are recommended as supplementary to radiography and will provide additional assurance that surface cracks are detected. Only cracks that are actually open to the surface (that is, cracks not covered by even the thinnest coating of metal, slag, dirt or other material) can be detected reliably by the penetrant methods; hence those methods are not recommended except for nonmagnetic weld metal to which the magnetic particle technique is inapplicable.

For the examination of welds in thin tubular structures, such as aircraft engine mounts, the interpretation and application of radiographic techniques are difficult because of the shape of such parts. For these products, the visual and magnetic particle techniques offer the best results for ferritic welds. For stainless steel or other austenitic welds in thin-walled tubular products, the dye or fluorescent penetrant technique should be employed as an aid to visual examination.

Ultrasonic tests have been omitted above because, for examination of weldments, they are still in a development stage. Ultrasonic techniques do appear promising for improved weld inspection.

Unsoundness Through Which Leakage May Occur. Regardless of the shape, size, thickness or kind of metal in a given weldment, the penetrant and pressure methods of inspection are recommended for the detection of leaks. Gas penetrants, employing helium or halogen gases and the associated gas

Table III. Typical Nondestructive Inspection Methods and Techniques

1 Penetrating Radiation	B Core loss
A Radiography	C Eddy current
(1) Photographic	D D-c potential drop
(2) Fluoroscopic	E Magnetic attraction
B Gaging	F Triboelectric
2 Sonic and Ultrasonic	5 Optical
A Pulsed echo (reflection)	A Visual
B Resonance	B Photo-electric
C Through-transmission	C Spectroscopic
D Damping	6 Thermal
3 Penetrant and Pressure	A Thermo-electric
A Liquid penetrant	B Temperature-sensitive material
B Gas penetrant	C Emissivity
C Pressure differential	7 Chemical
4 Magnetic and Electrical	A Macro etch
A Magnetic leakage, including magnetic particle tests	B Chemical spot tests
	C Spark test (steels)

detection apparatus (leak detectors), are without doubt the most effective of the three techniques. Such leak detectors are also relatively expensive, but, depending on the quantity of work and other factors involving fast operation and convenience, they actually may be the most economical for many test problems.

The simplest of the techniques in operation and equipment is the dye or fluorescent liquid penetrant technique. Both the gas and liquid penetrant techniques have an advantage over the pressure drop or differential test because they can pinpoint the source of a leak so that repairs may be made. In some production situations where continuous production testing is involved and where the shape of the units to be tested may cause difficulty in applying the gas or liquid penetrants, the pressure differential technique may prove more convenient and economical. Thus, gas penetrants are the most sensitive and the fastest, and liquid penetrants the most simple to handle. Final selection rests primarily on economic considerations peculiar to the individual inspection problems.

Detection of Cold Shuts in Cast Bronze Bushings

This example deals with cold shuts in Cu-Pb-Sn bushings, cast in "trees", with each small cored bushing at the end of its own individual feeder. Low pouring temperature minimizes lead segregation but increases the probability of closely knit cold shuts. When these cannot be tolerated in service, an effective nondestructive inspection method is necessary.

Magnetic, electrical and thermal methods are inapplicable. The size and shape of the part, as well as the orientation of the defect, usually rule out ultrasonic, X-ray, visual, macro-etching and ordinary liquid penetrant methods.

The recommended method is a technique of vacuum impregnating a fluorescent penetrant into the bushings, then examining them under ultra-violet light as the penetrant is driven out by heat.

Nondestructive Inspection of Heat-Resisting Metals

Because the majority of heat-resisting metals are used either in aircraft (where weight considerations keep the factor of safety to a minimum) or highly stressed apparatus requiring long life and dependable service (such as steam turbines, boilers and heat exchangers), the inspection standards are usually more exacting.

Radiography, ultrasonic inspection, magnetic particle testing, and the fluorescent and red dye penetrant methods of inspection are the commonly used nondestructive tests applied to heat-resisting metals.

In the radiographic inspection of heat-resisting metals, there is a group of high temperature alloys (which includes, for example, cobalt-base castings) for which a copper filter technique is employed when low-voltage X-rays (250 kv and under) are used on precision-cast parts, such as diaphragm partitions and gas turbine buckets. The copper filter eliminates or greatly

reduces the number of indications resulting from grain boundaries. The grain boundary indications make interpretation of the radiographs difficult and sometimes questionable. Grain boundary indications still present with the copper filter technique can usually be more positively identified as grain boundaries and therefore do not interfere with an accurate interpretation of indications resulting from defects. Although there may be a slight decrease in sensitivity with the use of copper filters, the interpretation of significant indications is unaffected when copper filters are used on these alloys.

Standard ultrasonic techniques are commonly applied to heat-resisting alloy billets, bar stock, and forgings. However, an increasing proportion of the ultrasonic testing applied to aircraft parts uses immersed testing equipment. With these techniques, the ultrasonic beam can be directed into fillets, complex surfaces and areas not flat enough for good contact with flat crystals. The ultrasonic beam can be directed at an angle to the surface, which improves the chances for detecting flaws that lie at an angle to the surface of the part. Also, this method permits the detection of flaws closer to the surface than does contact scanning.

Whereas 10 megacycles is the maximum practical testing frequency for standard contact scanning, frequencies up to 25 megacycles can be used in immersed testing techniques. These higher frequencies provide a narrower beam which can more accurately locate a defect and outline its configuration, which is particularly desirable in the inspection of many critical aircraft parts.

Magnetic particle inspection is often used in disclosing the manufacturing stage at which defects are formed in magnetic alloys. It is also used as a final inspection method, and to detect service damage. Since magnetic particle inspection is primarily a surface test, it is frequently used in conjunction with the internal inspection methods, X-ray and ultrasonic testing. This method of inspection is especially important in the detection of surface flaws in magnetic parts subjected to cyclic loads at elevated temperatures where fatigue failures may otherwise occur. Typical heat-resisting parts given magnetic particle inspection are steam turbine buckets, compressor blades, and bolting material.

Many heat-resisting alloys are non-magnetic, and therefore require either a fluorescent penetrant or a red dye penetrant method of inspection for surface flaws. Unlike magnetic particle inspection, these two types will produce indications only of flaws which are open to the surface.

In the fluorescent penetrant methods two developers have been available—a dry powder which is usually dusted on the specimen to develop the indication, and the wet developer applied by dipping. The dry powder provides greater sensitivity and should be used when fine shallow flaws are of prime importance.

A relatively new fluorescent penetrant method, known as the "post emulsification" method, offers additional increased sensitivity. In this method, the emulsifier is applied to the part after it has been soaking in the liquid pene-

trant, thereby making it water washable without decreasing the penetrability of the oil. The post emulsification method is recommended for most critical applications involving nonmagnetic heat-resisting alloys.

The red dye penetrant method is similar to fluorescent penetrant inspection except that the indication is shown as a brilliant red against a white background instead of as a fluorescent yellowish green against a neutral purple background. The developer, a chalk suspended in alcohol, is usually applied by spraying or brushing. Unlike fluorescent penetrant inspection which requires an ultra-violet light, the red dye indications can be observed under normal lighting.

Typical parts inspected by fluorescent and red dye penetrant methods are turbo-supercharger buckets, wheels, rotors and diaphragms, gas turbine buckets, rims, and rotors, special turbine valves and bolts, sheet metal seam welds, and miscellaneous accessory gas turbine parts.

Other types of nondestructive tests used to keep high-temperature alloys separated during processing are magnetic core loss, eddy current and thermo-electric methods. These instruments can be used in the forge shop, machine shop, stock areas, or any other areas where alloys may become mixed. The test is fast and simple, and consists of inserting a part or portion thereof in a test coil and observing the effect on an established instrument. Sorting techniques are discussed on page 163.

Determination of Soundness in Aircraft Turbine Disks

In this problem, ordinary sampling and destructive testing to determine the soundness is out of the question because of the size and cost of the forgings, the ineffectiveness of destructive tests, and the importance of checking every piece.

Penetrating radiation is not suitable because its sensitivity is too low to detect the flaws most likely to be present in forgings. Electrical methods also lack the necessary sensitivity, and magnetic methods cannot be used because the highly alloyed materials are non-magnetic or only weakly magnetic. Thermal methods are not applicable. Thus, some form or combination of sonic or ultrasonic, penetrant and pressure, optical, or chemical testing must be used. With forgings such as these, weighing up to nearly half a ton and costing up to a thousand dollars apiece, a combination of several methods in succession is well justified.

An efficient combination is: (1) macro-etching or electrolytic etching the rough forging, with visual examination for laps and other gross defects; (2) ultrasonic testing, to look for heterogeneities of grain size, bursts, pipe and segregation; (3) after rough machining or final machining, or both, a liquid penetrant test with thorough visual examination. These latter inspections of the surface of the metal are especially important because it is the surface which is usually most highly stressed. Sometimes, chemical spot tests may be used at any point to confirm that the correct alloy is being processed.

Sorting Mixed Lots of Steel

The occasional mixing of undesirable lots of steel with normal stocks requires all the skill of the engineer in working out an acceptable sorting technique. Two conflicting requirements influence the choice of an inspection method.

- 1 Cost of inspection must be low per piece
- 2 The method must be sensitive enough to detect differences positively, and nondestructively if finished parts are being sorted

The following examples outline successful and unsuccessful nondestructive methods used in large-volume sorting of mixed lots of steel.

Cracks in Thick-Walled Tubing, Medium Carbon Steel. This example assumes a defective lot, as received, containing cracks on the inside surface of steel tubing. The defects can be detected positively only after the steel has been machined, carburized, quenched, tempered and finish ground. In carburizing, carbon penetrates the cracks, causing breakage of some pieces.

Metallurgical examination shows most of the cracks to have a depth about one-third the wall thickness and to be extremely fine with no decarburization or oxide film apparent. An electrical conductivity test indicates that the cracks were formed at some elevated temperature and on cooling contracted to form a nearly perfect electrical contact across the crack at room temperature. Some magnetic or electrical method, therefore, appears to be most suitable. Sonic and ultrasonic tests may be impractical because of size limitations for ultrasonic transducers and lack of sensitivity in the damping of sonic vibrations. Radiography is unsuited because of the form and shape; liquid penetrants and magnetic particle tests are impractical for cracks inaccessible for visual examination. Magnetic tests may be applicable, in which the tubing is moved uniformly through a coil, with the core loss of an induced high-frequency alternating current through the coil windings indicated on an electrical meter. Several commer-

cial instruments are available for such a test, varying only in the electrical circuit and the flexibility or sensitivity. Some of these are more sensitive to variations in the dimensions of the test part than others; for instance, the core-loss method may be unsatisfactory when variations in wall thickness are as much as 0.002 in., since this much variation may give the same indication as the cracks.

This example illustrates one of the most difficult problems, where the final selection depends on highly specific factors such as exact details of a processing sequence or the precise dimensional tolerance on some dimension of a mill product, or the accessibility of crack location to visual examination. It also illustrates that, despite the wide variety of instruments available, there may be no suitable method except a prohibitively costly adaptation of an already complex technique.

Mixed Lots of 8620 and 1030 Steel Bar Stock. Magnetic core-loss methods are suitable, provided certain requirements are met:

- 1 Metallurgical process variables must be small
- 2 The difference in chemical composition must be appreciable or its effect on metallurgical structure quite marked
- 3 Magnetic test equipment must be flexible enough to permit choice of optimum frequency and optimum sensitivity of the detector

The metallurgical processing variables include the method of making the steel, particularly variations in deoxidation; mill fabrication procedures, especially the hot finishing temperature; and other inherent structure-sensitive properties of the metal. Large variations in metallurgical factors often cause core-loss indications exceeding the effect of chemical composition at any one frequency. Chemical composition variations affect the core loss but the magnitude of the effect varies with the frequency and is a maximum for a specific frequency and a specific variation of a chemical element. By varying the frequency of the magnetic testing device, metallurgical processing

variables can often be minimized so that the measured variation will reflect only the differences in chemical composition. These factors cannot be precisely defined for all conditions; however, variations in carbon and chromium contents within the range of this problem do produce significant effects on the core loss measured at optimum frequency.

The thermo-electric test, depending on the thermocouple effect of dissimilar metals, may be applicable; the method is new and its limitations in chemical sorting are not well known.

Tribo-electric devices depend on a peculiar surface contact condition which can be detected electrically. Results of sorting with this technique are largely empirical and require on-the-spot testing for proper evaluation of its usefulness.

Chemical test methods are probably the most reliable and foolproof for sorting mixed steels of the two types described. The spot test for chromium or molybdenum is adequate for separation of the two steels but the time factor and delicacy of the test eliminate it from consideration. Spark testing requires considerable experience and with such small differences in composition, tests by inexperienced inspectors are inconclusive.

Portable spectroscopic equipment is available for rapid visual identification of steel samples. Although such a test, which involves arcing of the test object, might be considered destructive on finished parts, the test is nondestructive on rough bar stock. Adjustments to detect a sensitive chromium or molybdenum arc line enable 8620 steel to be identified quickly.

For separating these two steels, the methods listed below are recommended in the order given:

- 1 Visual spectroscopic
- 2 Magnetic core loss
- 3 Tribo-electric
- 4 Thermo-electric

The last two methods depend on favorable empirical conditions and require preliminary trials with known samples.

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Metallography

By the ASM Committee on Metallography

THIS ARTICLE supplements the 1948 Metals Handbook by presenting seven topics on metallographic technique and equipment not covered in that edition.

First comes a discussion of the metallurgical microscope. This instrument, long highly developed and used in all metallurgical science and industry, is considered here in terms of the optical principles determining its successful use. Three applications are described after the discussion of principles.

The remainder of the article deals with specialized polishing and etching methods, and a summary of principles and application of the electron microscope. Extensive tabulations of electrolytic polishing and etching methods are presented on pages 170 to 173.

The Metallurgical Microscope

The principal parts of a modern metallurgical microscope are the illuminating system, the vertical illuminator, the aperture and field diaphragms, and the objective and eyepiece that comprise the image-forming system.

Illuminating System. The illuminating system consists of a light source of moderate to high intensity (for example, a ribbon filament bulb, zirconium arc lamp, or a carbon-arc source) and a condensing lens system. This condensing system, in conjunction with the microscope objective, focuses the light source (as in so-called "critical" illumination) or an illuminated condensing lens surface (as in Köhler illumination) nearly coincident with the specimen surface. Under such illumination a portion of the object surface is uniformly and intensely illuminated, a requisite to good image quality.

Vertical Illuminator. The conventional form of illumination employed for metallographic observations is known as bright field illumination—a condition of lighting that renders a dark image on a bright, well-lit background field. This is in contradistinction to special forms of illumination, such as dark field.

In bright field illumination, the light from the source, as illustrated in Fig. 1, passes into the vertical illuminator which contains either a total reflecting prism or a plane glass reflector inclined 45 deg to the axis of the incident light. Either of the reflectors is mounted directly in the rear of the microscope objective, and serves the purpose of deviating the incident light from the source into the objective and onto the specimen surface.

The principal use of the prism reflector is to render a more brilliant image than can be secured with the plane glass reflector. This is achieved because the prism reflects virtually all of the light incident upon it onto the object surface. Its use, however, reduces the potential resolving power of

Subdivisions	Page
The Metallurgical Microscope	164
Phase Contrast	165
Ultraviolet Metallography	166
Photomicrography	167
in Color	167
Electrolytic Polishing and Etching	169
Cathodic Vacuum Etching	169
Electron Metallography	174

the objective by about one half, and hence it should be used at magnifications lower than about 100 \times .

The plane glass reflector does not effect resolution, but produces an image less brilliant than that secured from the prism reflector. This lower brilliancy arises from greater light losses encountered each time the light is incident on the reflector, and the losses may be as high as 80%. This notwithstanding, the image is usually bright enough for comfortable observation.

Aperture Diaphragm. Appropriately positioned in the illuminating system is an iris diaphragm whose principal purpose is to regulate the amount of light incident on the specimen surface. An image of the diaphragm is formed in the rear focal plane of the objective and in consequence the amount of light entering the objective to illuminate the specimen can be controlled readily. Particular attention must be paid to proper adjustment of the aperture diaphragm so as not to impair resolution of the image-forming system.

It is a well known optical principle that the resolution of an objective system depends on the numerical aperture of the objective and the wavelength of light illuminating the specimen. The numerical aperture, which is related to design of the objective, is a measure of the light-gathering power of the objective system. Objectives of increasing numerical aperture possess inherently greater resolving power; for any given numerical aperture the resolution of fine object detail increases with decrease in wavelength of the illumination. The full resolving potentialities of the system, however, will be realized theoretically only when the pencil of light entering the microscope objective (as controlled by the aperture diaphragm) completely fills the rear lens of the objective. Actually, however, at full aperture the marginal aberrational errors of the objective become so pronounced, and the internal glare and reflections within the microscope system are so serious, that the improvement in resolution falls short of that which should theoretically be achieved. Because of these circumstances the aperture diaphragm is best set by visual observation of the specimen image, and so adjusted that the best possible resolution is obtained with a minimum of image glare.

Field Diaphragm. The field diaphragm is so located in the optical system that the diaphragm opening is imaged in the plane of the specimen surface. Its purpose is to reduce internal flare within the microscope system and, in consequence, to improve image quality and contrast. Because of the location of the field diaphragm image, as compared to that of the aperture diaphragm, adjustment of the field diaphragm will have no real effect on resolution. To contribute to best image quality in visual examinations, the diaphragm should be closed to an extent where the diaphragm image just begins to enter the field of view.

Microscope Objectives. The image-forming system consists of the objective and eyepiece whose primary purpose is to resolve specimen detail too small to be resolved by the unaided eye, and to enlarge subsequently such resolved detail for comfortable observation.

Metallurgical-microscope objectives may be conveniently divided into five general groups—achromats, semi-apochromats, apochromats, monochromats (for ultraviolet use), and a special group known as reflectors (see page 167). All microscope objectives represent a compromise in the degree to which various optical errors have been corrected. Among the most important errors are chromatic and spherical aberrations, coma, astigmatism, inadequate vertical resolution, and lack of flatness of field.

Modern objectives, as well as eyepieces and other optical parts in the microscope, are coated with a low-reflectance material to improve image quality through reduction of spurious light reflections and consequent flare at air-glass surfaces.

Achromat objectives are relatively low in cost and perform well when appropriately used. As a group, they are not so completely corrected for chromatic and spherical errors as are semi-apochromats and apochromats, and in consequence are unable to render an image that possesses true color relationships. They perform best in conjunction with illumination appropriately filtered to supply wavelengths of light at about the middle of the visible spectrum.

Apochromatic objectives are the finest objectives obtainable, and because of the high degree of optical correction, their cost is relatively great. In general, this class of objectives has higher numerical aperture and initial magnification than achromats, but renders an image that is inferior in flatness of field. Because of the high degree of correction for chromatic and spherical aberrational errors, apochromats are most desirable for use at high magnifications and they perform efficiently when used with white light, light of daylight quality, green-yellow, or blue illumination.

Semi-apochromats are a compromise between achromatic and apochromatic objectives with respect to residual optical errors. In general, they approach the performance of apochromats.

Microscope Eyepieces. The purpose of an eyepiece or ocular is to enlarge the primary real image formed by the objective and to render it visible as a virtual image, or to project the objective image as a real image, as in photomicrography. Some eyepieces are pur-

Supplements the articles on pages 159 to 164 of the 1948 ASM Metals Handbook

posely overcorrected to improve image quality, as, for example, the compensating type of eyepiece which compensates for the residual color errors in semi-apochromatic and apochromatic objectives. As contrasted to oculars designed for visual use, eyepieces of a true negative character may be employed for image projection, as in photomicrography, to render an image of exceptionally flat field. These eyepieces, because of their design, cannot be used for visual observations.

Geometric Microscope-Image Formation. As illustrated in Fig. 1, illumination from an appropriate source is collimated by the condensing system and directed by the plane glass reflector (vertical illuminator) downward and through the objective onto the surface of the specimen. Under such circumstances, as mentioned heretofore, the objective serves to converge the light beam and to illuminate a small area on the object specimen.

If the microscope is adjusted by focusing, so that the object surface is positioned just outside the equivalent front focal point of the objective, as in Fig. 1, a primary real image of greater dimensions than the object field will be formed within the microscope tube. By critical focusing, this primary image may be positioned at the focal point or within the focus distance of the eyelens of the eyepiece system. The eyepiece illustrated in Fig. 1 is a conventional Huygenian-type ocular, whose field lens, as indicated, assists the objective in forming the primary real image. If the entrance pupil of the eye is now made coincident with the exit pupil of the eyepiece, the cornea lens of the eye in conjunction with the eyelens of the ocular will form an enlarged image of the primary real image on the retina of the eye. Owing to physiological response attending excitation of the retina, the image will appear to exist in space at approximately the near point of the eye (250 mm) for a mature observer of normal sight. This space image is known as a virtual image, since it has no real existence.

By readjusting the focus of the microscope so that the primary real image is positioned outside the focal point of the eyelens, there will be formed a second real image. This may be observed, as in photomicrography, by intersecting the image-forming rays of light by a reflecting or ground-glass screen.

Principles of Phase Contrast Metallography

Illumination incident on a metallographic specimen may be locally altered in phase upon reflection by differences in optical path attending small-order vertical displacements on the specimen surface; by existing differences in surface optical activity between structural phases of different compositions; and by the normal consequence of metallographic etching and the selective formation of reaction-product films differing in thickness or refractive index or both.

In conventional microscopy, the mere existence of such phase differences in the components of the reflected light in no way contributes uniquely to contrast in the final image, since the human eye is incapable of distinguishing

between light differing only in phase. In phase contrast, however, these small differences in phase are transformed into corresponding modulations in light intensity which may greatly affect image contrast in the final image plane. Therefore, this optical technique can render visible an element of structure that introduces locally a change in phase of the reflected light, even though this structural element is normally invisible microscopically because of insufficient optical contrast.

For the purpose of illustration, consider a metallographic specimen containing a small discrete element of structure that is depressed from the surface of the surrounding matrix by an amount equivalent to about 1/20 the wavelength of light illuminating the specimen. The incident light upon reflection from the depressed structural element will be retarded in phase with respect to the light reflected from the matrix, owing to the greater optical path at the depression. Furthermore, the incident light will be diffracted at the matrix discontinuity in the region of the depression, and a portion of this diffracted light will be reflected and continue on its undeviated course into the microscope objective. This is re-

ferred to as the undeviated reflected light. The remaining portion of the diffracted light will be deviated at various angles from the direction of reflection at incidence, and it is referred to as the deviated or diffracted light. The amount and intensity of the light deviated depends on the character of the specimen structure.

The undeviated light, and all diffracted orders of the deviated light falling within the angular aperture of the objective, will be refracted by the objective to the image plane where, by intensity interference effects, the light distribution may resemble that of the specimen structure. Precisely how faithfully the image will resemble the object structure will depend on how much of the diffracted light the objective collects. In order to achieve ideal representation of the light distribution across the object plane, all of the diffracted orders must be collected; to secure any resolution of the structure, at least the first-order diffraction maximums on either side of the undeviated beam must be collected.

It may be shown by wave diagrams or by vector analysis for the example cited that the deviated light on the average is retarded in phase by $\lambda/4$

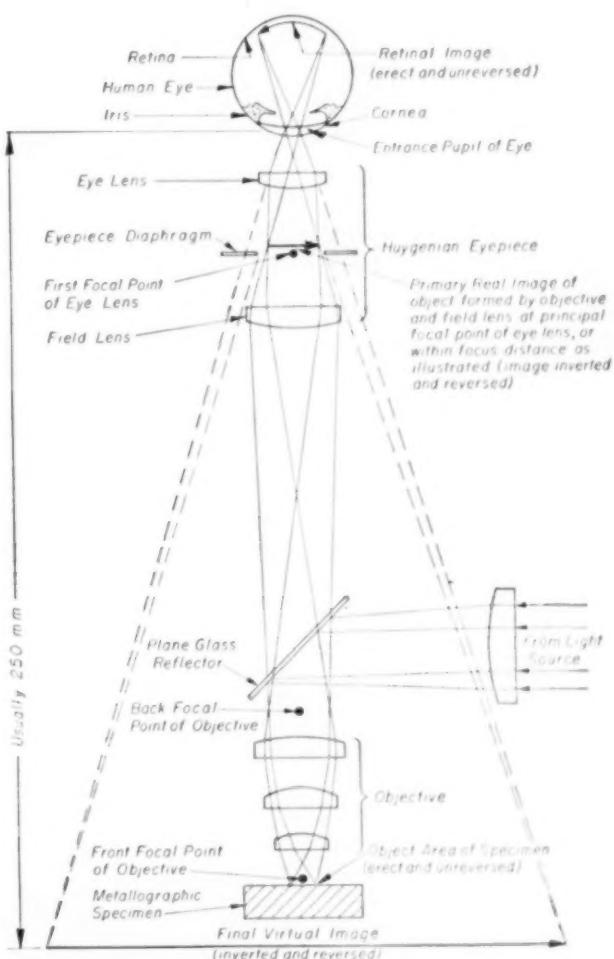


Fig. 1. Trace of Light Rays through the Metallurgical Compound Microscope from the Object Field to the Final Virtual Image

(90 deg) with respect to the undeviated light. Furthermore, the light reflected from the depressed structural element is in reality equivalent to the sum of the deviated and undeviated light waves.

In formation of the image of the structural element by interference effects between the undeviated and deviated light, it is significant to note that the existing difference in phase between the two in no way contributes to image contrast. However, in a manner to be described, phase contrast uniquely separates the undeviated from the deviated light, and subsequently introduces a further, but controlled, shift in phase between the two. Depending on the amount of phase difference artificially introduced, the interference between the undeviated and diffracted light may be either constructive or destructive, resulting in the image of the structural element being respectively either brighter or darker in contrast to the surrounding matrix.

Phase Microscope. The principle of the phase contrast metallurgical microscope is illustrated in Fig. 2. Under appropriate conditions of illumination (Köhler illumination), an image of the light source is formed at, or very near, the plane of the aperture diaphragm. If in this plane an annular diaphragm is inserted normal to the incident light as illustrated, the diaphragm will be imaged in the rear focal plane of the objective. This real image, because of its location, will be imaged at infinity by the objective.

Upon reflection from the specimen surface, the image will once again be imaged upon itself in the rear focal plane of the objective system. All of the undeviated reflected light from the specimen surface will therefore be defined in the rear focal plane of the objective by the annular diaphragm image, whereas the diffracted light received by the objective will be unrestricted in procession to the final image plane. By this arrangement, an effective means is provided for separating the undeviated light from most of the diffracted orders, and gives opportunity to alter artificially the phase relationship between the two.

In phase contrast metallography, it is customary to retard the undeviated light with respect to the deviated light. This is achieved by inserting a phase plate in the region of the rear focal plane of the objective, as illustrated in Fig. 2. The phase plate consists of a clear slip of glass onto which is deposited an annulus of magnesium fluoride whose shape and size correspond to the image of the annular diaphragm. If the annulus and diaphragm image are made to coincide, then the undeviated light passes through the annulus and is thus retarded in phase, whereas the deviated light passes mainly through the clear portions of the phase plate, and is relatively unaltered in phase.

If the magnesium fluoride annulus is of such thickness that the undeviated light is retarded by $3\lambda/4$ (270 deg) for a given wavelength of light (usually green-yellow for metallographic work), then the undeviated and deviated light interfere destructively in the image plane to form the image of the depressed structural element. This results in the element appearing darker than the surrounding matrix. In this

example, and in others where the element of structure causing a retardation in phase of the reflected light appears darker than the matrix in the final image plane, the observation is known as *positive* or *dark* phase contrast.

Negative or bright phase contrast is secured by employing a phase-altering annulus that will retard the undeviated light by $\lambda/4$ (90 deg), thereby causing an element of structure that initially retards the reflected light to appear brighter than the matrix in the final image. In principle this is achieved through constructive interference between deviated and undeviated light owing to the $\lambda/4$ (90 deg) phase shift.

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etching, the phase contrast image must be regarded as arising not only from phase contrast effects, but also from bright field effects caused by differences in reflection coefficients, and to dark field and conical illumination effects arising respectively from gross light scattering and the use of an annular diaphragm as mentioned.

Coupled with these complexities, it is difficult at times to discriminate between the phase contrast effects arising from small vertical displacements existing on the specimen surface and other phase effects arising from the normal consequence of metallographic etching. Because reaction product films affect the phase of reflected light in unpredictable ways, phase contrast can be applied with greatest assurance to the examination of unetched specimens, to those cathodically vacuum etched, or to specimens whose structures are difficult to reveal fully by conventional or special etching techniques.

Because of the sensitivity of the phase contrast method, it offers possibilities as a device for the qualitative study of surface finishing, and in the study of certain metallographic phenomena attending deformation or phase changes accompanied by small-order disruptions on the surfaces of prepared specimens.

Ultraviolet Metallography

Compared to the use of visible radiation to illuminate the object specimen, ultraviolet radiation is advantageous because it improves resolution and reduces flare within the microscope system.

Improvement in resolution through the use of wavelengths of radiation shorter than those comprising the visible spectrum is more desirable than

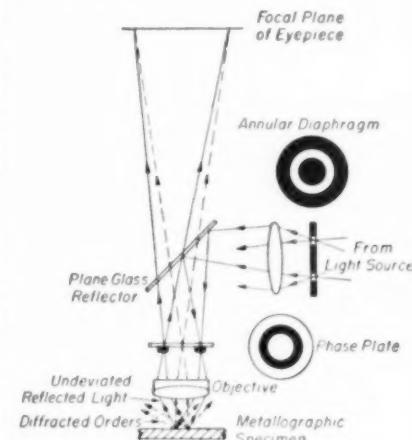


Fig. 2. Trace of Light Rays through the Phase Contrast Metallurgical Microscope

the alternate approach of increasing the numerical aperture of the objective system. The latter is always accompanied by undesirable effects, namely, deterioration in flatness of field and vertical resolution, and increasing difficulties in securing optimum focus of the image.

The extension of metallography to

the use of short ultraviolet radiation, makes necessary the use of special optical equipment. Conventional optical glasses do not transmit wavelengths shorter than about 3500 Å. Furthermore, the human eye does not respond to radiation below about 4000 Å, thus requiring that the ultraviolet image be converted into an image of longer wavelengths by fluorescent or photographic methods.

Refraacting Components. For application in ultraviolet microscopy with wavelengths shorter than about 3500 Å, objectives, eyepieces, and other optical parts of the microscope are constructed of quartz, fluorite, lithium fluoride, or other transparent materials having appropriate transmission characteristics.

To enable focusing of the image prior to photomicrography, refracting objectives must be achromatized at two different wavelengths. This correction is made for a selected wavelength in the visible spectrum and at some designated shorter wavelength in the ultraviolet for photomicrography. Such objectives are described in the three references on this subject, page 177.

L. V. Foster has discussed the use of ordinary, but well corrected refracting objectives for use with radiation wavelengths in the near ultraviolet (3650 Å). Inasmuch as such objectives are achromatized at only one designated wavelength in the visible spectrum, focusing of the ultraviolet image is carried out directly by viewing the image with the infrared image tube of a 1P25 Sniper-scope. Although this instrument was designed originally for peak sensitivity to infrared radiation, it is also responsive to ultraviolet radiation of about 3650 Å.

Inasmuch as residual chromatic aberration in refracting objectives becomes more pronounced at short wavelengths of radiation, they must be used with essentially monochromatic radiation. This circumstance is not always a desirable one; broad band radiation would sometimes be more advantageous.

Reflecting Components. The outstanding characteristics of simple re-

flecting objectives, illustrated in Fig. 5, are (1) inherent freedom from chromatic aberration at all wavelengths of radiation, (2) a lesser amount of spherical aberration compared to a refractor of equivalent diameter and focal length, and (3) the circumstance that reflecting objectives can be designed to possess a reasonably long working distance. The latter is advantageous for examining irregularly shaped fractures at moderately high magnifications, hot-stage observations, metallographic examination of irradiated metals and alloys, and in circumstances requiring more-than-normal working distance.

In ultraviolet metallography, and where infrared microscopy is desired, the reflecting objective is ideally suited because of its achromatic characteristic. By the use of such an objective, the metallographic image may be focused critically at any single or any group of wavelengths within the visible spectrum with assurance that the image will remain in focus when subsequently photographed under ultraviolet or infrared radiation. The former quality of radiation is readily secured by appropriately filtering the radiation emitted from a conventional ultraviolet lamp; the latter, from a filtered carbon-arc source with the water-cooling cell removed from the radiation path.

Reflecting objectives of relatively high numerical aperture, and in particular those designed for use with an immersion component, contain one or more refracting elements of quartz or similar optical material. The introduction of these components, however, is at the sacrifice of complete achromatism at all wavelengths.

The excellent performance of a simple reflecting objective at radiation wavelengths of 5700 Å (green-yellow) and 3650 Å (near ultraviolet) is illustrated in Fig. 6. In the photomicrographs secured with ultraviolet radiation, the projected image was focused by utilizing the visible radiation emitted by a General Electric mercury-arc source (Type H-4), and the image was subsequently photographed with a

wavelength of 3650 Å. The 3650 Å spectral line was isolated by filtering the radiation with a Corning 5860 glass filter.

Photomicrography in Color

The availability of a variety of color photographic emulsions of high resolving power, and the comparative ease by which these emulsions may be processed in the laboratory, has been responsible for rather widespread interest in color photomicrography. Aside from the aesthetic value, photographic

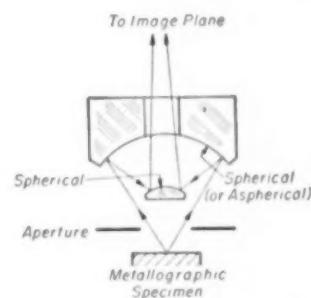


Fig. 5. Trace of Light Rays in the Simple Reflecting-Type Objective. Rays incident on the specimen surface are omitted for sake of clarity

recording in color is of interest in non-ferrous metallography where a variety of highly colored metallographic structures are encountered, in corrosion studies where the color of reaction products is of comparative significance, and in general applications where the color of a phase or phases is necessary for proper identification.

Metallography in color is best carried out with well corrected objectives and other optical parts, and with particular attention to spectral quality of the illumination, setting of the field and aperture diaphragms, photographic ex-

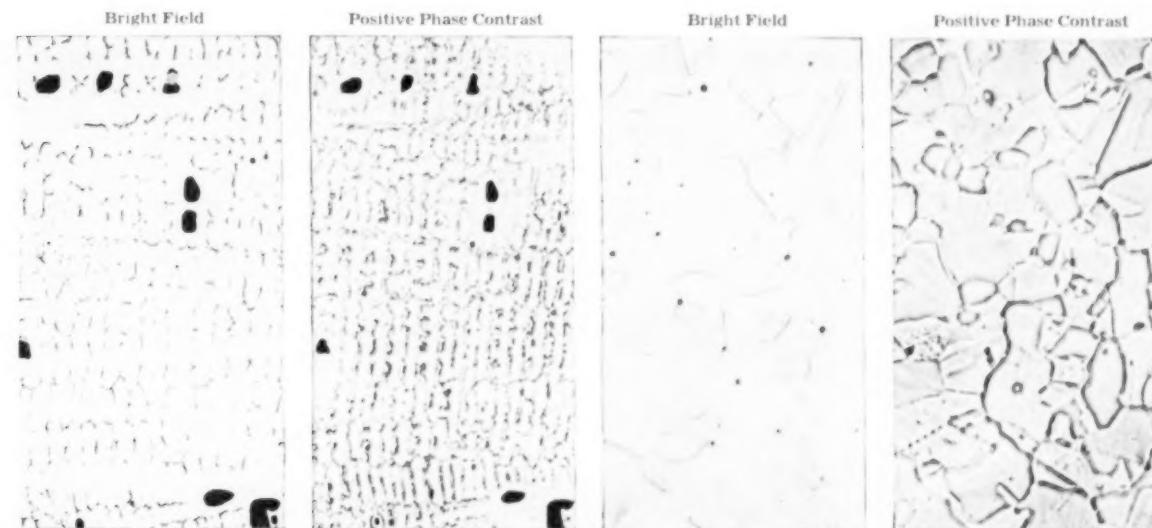


Fig. 3. As-Cast Alpha Brass under Bright Field Illumination and Positive Phase Contrast. 100×. Etched in ammonium hydroxide, hydrogen peroxide and water

Fig. 4. Commercially Pure Nickel, Cathodically Vacuum Etched for 2 Hr at 1800 Volts, 25 Milliamperes, in an Argon Atmosphere at a Pressure of 17.5 Microns. 250×

posure, and development of the color emulsion.

Quality of Illumination. As a general principle in color photomicrography the quality of the illumination incident on the specimen surface must be comparable to the spectral energy distribution for which the photographic emulsion is balanced. It is only under this condition that the colors in the specimen object will be ideally reproduced in the color photomicrograph. However, acceptable color reproductions of a variety of structures can be secured through the use of appropriate color emulsions and a carbon-arc illuminating source unfiltered except possibly for the removal of excess ultraviolet radiation.

The best source of illumination for color photomicrography is a carbon arc. Such a source, compared to a ribbon filament lamp, is highly reproducible with respect to average "color temperature", even though the radiant energy forms a continuous spectrum superimposed on a continuous background. In the spectral region of 3400 to 4300 Å, the emission is high, generally necessitating the removal of all the ultraviolet radiation by filtering except for the normal component required for the particular color temperature desired. The approximate effective color temperature of various carbon-cored arc sources is given in Table I.

For any particular arrangement of the metallograph, the color temperature of the illuminating source may be measured by one of several available color temperature meters, such as the Harrison meter. By photometric filters accompanying such a color meter, the color temperature of the source may be raised or lowered to match that of the color emulsion used.

Because of selective chromatic absorption by the glass components of the microscope system and the introduction of spurious colors arising from residual chromatic errors in the condensing lenses, the spectral quality of the illumination incident on the specimen

surface may be different from that of the source which was initially adjusted to match the photographic emulsion. This total color imbalance may not be significant at a magnification of about 100 diameters. However, for the most critical work at moderate and high magnifications the noticeable color deficiency in the image may be eliminated by compensating filters.

Photographic Exposure. The latitude of photographic exposure of color emulsions is narrow and hence to secure proper color rendition in the final photomicrograph the correct exposure time must be known accurately. Conventional photographic exposure meters are not suitable in photomicrography. Comparative methods with black and white trial-exposure standards have been described in "Symposium on Metallography in Color", ASTM Special Technical Publication 86, 1948.

Table I. Effective Color Temperature

Direct Current, amp	Anode Diameter, mm	Effective Color Temperature, °K
4.5	8	3645
5	8	3680
5	6	3750
10	8	3820
10 ac	6.4	3475

Color Emulsions. Of the various color emulsions available, the single-exposure type is usual in color photomicrography because of convenience in photographic exposure and processing.

Color emulsions in the form of cut film suitable for the purpose are Eastman Kodak Ektachrome (daylight) and Ansco Color (daylight), balanced at color temperatures of 5900 K; Ektachrome B and Ektacolor B at a color temperature of 3200 K; and Ansco Color (tungsten) at 3400 K. Although not so convenient from the standpoint of size and flexibility in handling, 35-mm Kodachrome daylight and Type A

(tungsten) may be successfully used. These emulsions, however, must be processed and developed by the film manufacturer.

A finished color photomicrograph may be obtained in the form of a color transparency or as a color print. In general, the procedure involving color printing (because of the multiplicity of operations) presents more possibilities for departure from true color balance in the final photomicrograph than in the more simplified processing of color transparencies. However, exceedingly high-quality opaque color reproductions can be secured if proper attention is given to details of the procedure.

Positive transparencies are secured directly through the use of Kodachrome, Ektachrome or Ansco Color emulsions. From these positive transparencies, opaque color prints may be obtained by printing on Ansco Printon paper, or through the more complicated process of color printing by the Kodak dye transfer method. Of the two reproduction methods, the dye transfer process is the more expensive and technically complicated, but renders by far the better color print with regard to brilliancy of colors and faithful color reproduction.

Alternate to printing of positive transparencies as described, but at the sacrifice of high-quality reproductions, a color "negative" of complementary coloring may be secured on Kodak Ektacolor emulsion. From this negative, positive transparencies may be obtained by printing on Ektacolor print film, or opaque color reproductions secured by the use of Kodak Pan Matrix film and a process similar to the dye transfer method.

Emulsion Processing. The processing of color emulsions in the laboratory is tedious but not difficult. It is imperative, however, to follow explicitly the recommendations of the manufacturer in order to secure satisfactory results. Processing directions are contained within the developing reagent kit appropriate for a given color emulsion.

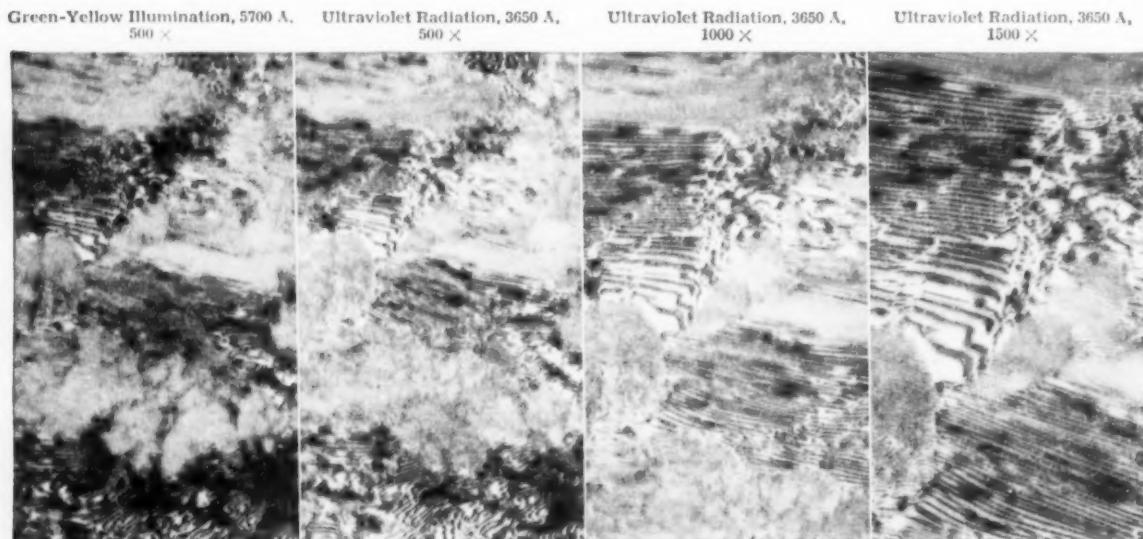


Fig. 6. Illustrating the Excellent Performance of a Reflecting-Type Microscope Objective at Different Total Magnifications and under Two Different Wavelengths of Radiation.

Electrolytic Polishing and Etching

Electropolishing is most useful in the metallography of stainless steels, copper alloys, aluminum alloys, magnesium, zirconium and other metals difficult to polish by conventional mechanical methods. The electrolytic technique can remove completely all traces of worked metal remaining from the cutting and grinding operations.

Electro-etching can develop easily and quickly certain structures extremely difficult to reveal by ordinary chemical etching.

Theory. An adequate but simplified theory of electrolytic polishing was developed by P. A. Jacquet in 1936. The mechanism is preferential solution of the "hills" or high flaws on the rough surface, such as result from grinding, until they are completely removed and the surface becomes flat and smooth. When such a rough surface is made the anode of an electrolytic circuit, it becomes coated with a viscous film of a complex salt solution formed by the reaction between metal and electrolyte. This layer of solution, known as the polishing film (Fig. 7), has a very high electrical resistance. The resistance at a peak *A*, represented by the distance *AB*, will be lower than at depression *C*, represented by the distance *CD*, be-

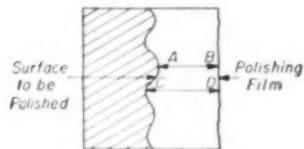


Fig. 7. Mechanism of Electro-polishing (P. Michel)

cause the film is thinner at *AB*. The current at *A* will be considerably higher than at *C*, causing the metal at *A* to dissolve until the surface becomes flat.

The actual stages of electropolishing vary in different electrolytes. The simple relationship where polishing occurs at any one of a continuous range of currents and voltages is shown in Fig. 8. At low voltages, a film forms on the surface and no current passes. At these lower voltages, etching occurs but not polishing. At higher voltages, polishing occurs. The perchloric acid baths used for aluminum conform to this relationship.

A more complex relation, frequently encountered, is shown in Fig. 9, and has the following stages: (1) the current density increases proportionately with the potential; some metal dissolves and the surface has a dull etched appearance; (2) the polishing film is formed; as the film builds up, the resistance increases and the current drops; (3) finally, the film reaches a point of equilibrium and polishing occurs; during this stage, current density remains constant even though the single-electrode potential is increased; and (4) a new reaction, usually the formation of gas bubbles, occurs in the electrolyte. These bubbles break the film and severe pitting occurs.

Electrolytes of the sulfuric-phosphoric acid and chromic-acetic acid types

used for stainless steels typify this four-stage relationship.

Apparatus and Procedure. The equipment used for electropolishing can vary from the simplest arrangement of dry cells to elaborate arrays of rectifiers and electronic control devices. Such apparatus is available commercially. The choice of equipment depends on the number and type of samples to be treated and the versatility and control desired.

Electropolishing and electro-etching apparatus consists of three essential

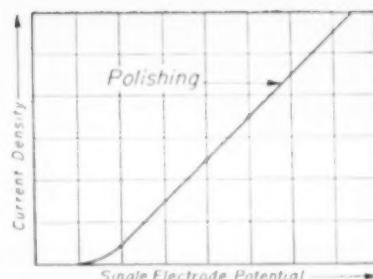


Fig. 8. Schematic Relation Between Current Density and Single-Electrode Potential for Solutions Having a Polishing Action over a Wide Range of Voltages and Currents (J. L. Waisman)

PRECAUTIONS

Because explosions have occurred with electrolytes containing acetic anhydride and perchloric acid, extreme caution is necessary in using them. Some companies prohibit the use of these solutions in their laboratories. Glacial acetic acid can usually be substituted for the acetic anhydride, thereby decreasing the danger of explosions. When glacial acetic acid is substituted, the characteristics of the bath may be slightly changed and the current density may have to be adjusted to obtain the desired results.

If acetic anhydride is used, the constituents should be mixed with great care. The anhydride should be added to the perchloric acid at a rate no greater than one drop in 10 sec. During this mixing and the subsequent polishing operations, the bath should be cooled by wet ice or by a mixture of dry ice and acetone. If at any time the temperature of the electrolyte rises above 75 F, all operations should be stopped until the temperature returns to normal. At no time should organic materials such as bakelite, cotton, wood or wool be allowed to come in contact with a bath of this type.

All of the recommended polishing and etching baths should be used in a hood to remove dangerous and disagreeable odors. Most of the solutions are corrosive and should not be allowed to come in contact with the skin.

parts: the current source, the electrolytic cell and the electrical controls. The source (batteries, d-c generators or rectifiers) should deliver a constant supply of direct current at 100 volts or more. Unless the setup is for extremely routine work, provision should be made for controlling voltage and current. Variable resistances of the slide-wire type are frequently used.

The cell is simply a dish containing the electrolyte, in which are suspended the cathode and anode. The cell is usually glass, but may be of wax-type material for solutions containing fluoride ions. Sometimes a stainless steel cell is used, which may serve also as the cathode. Frequently, the cell is

surrounded by water or some other coolant. For many applications, a stirrer in the electrolyte is necessary.

The cathode will vary with the reagent and the sample to be treated. It may lie horizontally on the bottom of the cell or may be suspended vertically a short distance from the anode. The sample to be polished serves as the anode; it should be arranged for quick removal from the solution. The electrical connection to the anode should be simple and easily broken so the sample may be rinsed immediately after polishing or etching.

Prior preparation varies greatly. Usually the sample is mechanically polished through 000 paper or its equivalent before electropolishing. For some applications, notably macro-examination, no grinding is necessary; however, electropolishing is usually most rapid on a finely ground surface.

Solutions most frequently used for electrolytic polishing and etching are summarized in Tables II and III. Only those baths of proven value for metallographic purposes are included.

Precautions to be observed with electrolytes containing acetic anhydride and perchloric acid are given in the box at left.

Cathodic Vacuum Etching

When a metal is made the cathode in a vacuum glow discharge system, subjecting it to bombardment by positive gas ions, some of the metal is ejected from the surface. The dislodged atoms diffuse through the gas and deposit on the walls of the vacuum system or on the electrodes. This process, called sputtering, has been used for many years

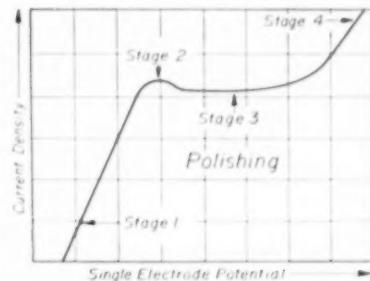


Fig. 9. Electrical Conditions for Electrolytes That Polish at a Nearly Constant Current Density (J. L. Waisman)

Table II. Recommendations for Electrolytic Polishing

Metal	Bath Composition	Temperature °C °F		Electrical Conditions	Cathode Material	Time	Remarks
Aluminum	7 parts perchloric acid★ 13 parts acetic anhydride	24	75	22 to 25 volts 0.01 to 0.02 amp./sq cm	Stainless steel	3 to 4 min	Should be stirred. Works best after 1 g per liter of Al is dissolved.
Aluminum	1 part perchloric acid (20%)★ 4 parts ethyl alcohol	24	75	30 to 80 volts 1 to 4 amp./sq cm	Stainless steel	10 to 60 sec	Stir to prevent over- heating. Good for alloys except those containing more than 2% Si.
Aluminum	1 part nitric acid (cone) 2 parts methyl alcohol	24	75	4 to 7 volts 1.0 to 2.8 amp	Stainless steel	20 to 60 sec	Mix reagents carefully. Used also for aluminum alloys.
Beryllium	3 parts orthophosphoric acid 1 part chromic acid	82	180	2.5 amp./sq cm	Lead or graphite	60 sec	Should be used under a hood.
Bismuth	1 part glacial acetic acid 1 part nitric acid 4 parts glycerol	24	75	12 volts	Stainless steel	1 to 5 min	Used also as an electrolytic etch.
Brass	3 parts orthophosphoric acid 5 parts distilled water	16 to 27	60 to 80	1.9 volts 0.13 to 0.15 amp./sq cm	Copper	10 to 15 min	Used for alpha brass.
Brass	4 parts orthophosphoric acid 6 parts distilled water	16 to 27	60 to 80	1.9 volts 0.09 to 0.11 amp./sq cm	Copper	10 to 15 min	Used for alpha-plus- beta brass. Not good for leaded alloys.
Bronze	2 parts orthophosphoric acid 1 part distilled water	21 to 24	70 to 75	10 to 20 volts 0.8 amp./sq cm	Stainless steel	10 to 20 sec	
Bronze	67 parts orthophosphoric acid 10 parts sulfuric acid (conc) 23 parts distilled water	24	75	2.0 to 2.2 volts 0.1 amp./sq cm	Copper	15 min	For bronze contain- ing up to 6% Sn.
Bronze	47 parts orthophosphoric acid 20 parts sulfuric acid (cone) 33 parts distilled water	24	75	2.0 to 2.2 volts 0.1 amp./sq cm	Copper	15 min	For bronze contain- ing more than 6% Sn.
Cadmium	45 parts orthophosphoric acid 55 parts distilled water	24	75	2 volts 0.05 amp./sq cm	Nickel	30 min	
Chromium	1 part perchloric acid★ 20 parts glacial acetic acid	24	75	45 volts 0.15 to 0.2 amp./sq cm	Stainless steel	3 to 4 min	
Cobalt	Orthophosphoric acid	24	75	1.2 volts	Stainless steel	3 to 5 min	Bath not agitated.
Copper	82.5 parts orthophosphoric acid 17.5 parts distilled water	24	75	1.0 to 1.6 volts 0.05 to 0.10 amp./sq cm	Copper	10 to 40 min	
Copper	3 to 4 parts orthophosphoric acid 6 to 7 parts distilled water	16 to 27	60 to 80	1.5 to 1.8 volts 0.06 to 0.08 amp./sq cm	Copper	10 to 15 min	Suitable for alloys except tin bronzes.
Lead	41 parts perchloric acid★ 151 parts acetic anhydride 8 parts distilled water	24	75	110 volts 0.1 amp./sq cm	Copper	15 min	Not entirely repro- ducible.
Lead and Lead Alloys	1 part perchloric acid (20%)★ 4 parts ethyl alcohol (96%)	38 max	100 max	18 to 25 volts 2 to 3 amp./sq cm	Stainless steel	10 sec	Good for pure lead (99.99%). Dangerous if overheated.
	1 part perchloric acid (20%)★ 4 parts ethyl alcohol (96%)	38 max	100 max	15 to 28 or 24 to 35 volts 3.0 to 7.5 or 4.0 to 7.5 amp./sq cm	Stainless steel	10 sec	Good for lead with 2 or 5% Sn.
				12 volts 1.5 amp./sq cm	Stainless steel	10 sec	Lead with 40% Sn.
				25 to 35 volts 3 to 4 amp./sq cm	Stainless steel	10 sec	33% Pb - 50% Sn - 17% Cd.
				2.5 amp./sq cm	Stainless steel	45 to 60 sec in 20-sec steps	Lead with 1% Sn, 1% Sb.
Magnesium	3 parts orthophosphoric acid 5 parts ethyl alcohol (96%)	24	75	1.5 volts 0.01 amp./sq cm	Stainless steel	3 to 5 min	
Magnesium	1 part hydrochloric acid 9 parts ethylene glycol mono-ethyl ether	2 max	35 max	50 to 60 volts	Stainless steel	10 to 30 sec	Bath should be stirred and kept cool.
Magnesium	50 parts perchloric acid★ 140 parts distilled water 700 parts ethyl alcohol	24	75	0.6 to 0.9 amp./sq cm	Nickel	60 sec	
Molybdenum	1 part sulfuric acid (conc) 4 parts distilled water	52	125	3 to 9 volts	Stainless steel	25 to 35 sec	Good for sintered molybdenum.
Molybdenum	5 parts hydrochloric acid (conc) 2 parts sulfuric acid (conc) 15 parts methyl alcohol (95%)	24 max	75 max	19 to 35 volts	Stainless steel	25 to 35 sec	Mix reagents carefully. Good for sintered & cast Mo. Use in ice bath. Avoid contamination with water.

*DANGEROUS. Before mixing or using this reagent, read the precautions given in box on page 169.

Table II. Recommendations for Electrolytic Polishing (continued)

Metal	Bath Composition	Temperature °C °F		Electrical Conditions	Cathode Material	Time	Remarks
Molybdenum	1 part sulfuric acid (conc) 7 parts methyl alcohol	24 75		12 to 18 volts 0.2 to 0.5 amp/sq cm	Stainless steel or platinum	30 to 90 sec	Mix reagents care- fully. For sintered or cast Mo or Mo alloys.
Nickel	39 parts sulfuric acid (conc) 29 parts distilled water	35 max	95 max	0.4 amp/sq cm	Nickel	4 to 6 min	Mix reagents care- fully.
Nickel	1 part perchloric acid★ 2 parts acetic acid	18 65		50 volts	Stainless steel	1 min	
Steel and Iron	1 part perchloric acid★ 20 parts glacial acetic acid	24 75		45 volts 0.2 amp/sq cm	Stainless steel	3 to 4 min	Good for ingot iron, carbon steel and stainless steel.
Steel and Iron	56 parts orthophosphoric acid 44 parts distilled water			0.15 to 2 volts 0.01 amp/sq cm	Iron		For iron and silicon iron.
Steel and Iron	2 parts perchloric acid★ 7 parts ethanol 1 part methylcellosolve or glycerine	16 to 32	60 to 90	5 to 15 volts 0.5 to 2.2 amp/sq cm	Stainless steel	0.5 to 2.5 sec 10 to 15 sec 20 to 30 sec	High speed steel. Carbon and alloy steel. Stainless steel.
Steel and Iron	5 parts perchloric acid★ 75 parts ethyl alcohol (95%) 14 parts distilled water	21 to 24	70 to 75	20 to 30 volts 1.3 amp/sq cm	Stainless steel	40 to 60 sec	Satisfactory for cast steels.
Steel and Iron	6 parts perchloric acid★ 94 parts ethyl alcohol	24 75		35 to 40 volts	Stainless steel	15 to 60 sec	Good for stainless steel.
Steel and Iron	1 part perchloric acid★ 2 parts acetic anhydride (Let bath stand 24 hr before use)	24 75		50 volts 0.06 amp/sq cm	Steel or aluminum	4 to 5 min	Good for austenitic steels.
Steel and Iron	185 parts perchloric acid★ 765 parts acetic anhydride 50 parts distilled water (Solution made 24 hr before use)	24 75		50 to 60 volts 1.5 to 2.5 amp	Stainless steel	0.5 to 2 min	For carbon and low- alloy steels.
Steel and Iron	1 part perchloric acid★ 4 parts glacial acetic acid	16 to 21	60 to 70	100 volts 0.2 to 0.5 amp/sq cm	Stainless steel	1 to 2.5 min	
Steel and Iron	1 part perchloric acid★ 10 parts glacial acetic acid	24 75		50 to 60 volts 1.5 to 2.5 amp	Stainless steel	0.5 to 2 min	For carbon and low- alloy steels.
Steel and Iron	19 parts glacial acetic acid 1 part chromic acid	17 to 19	62 to 66	20 volts 0.4 amp/sq cm	Stainless steel	Several minutes	
Tin	63 parts perchloric acid★ 300 parts glacial acetic acid 12 parts distilled water	24	75	2 to 30 volts 0.1 to 0.15 amp/sq cm	Tin	10 min	Not always repro- ducible.
Tin	194 parts perchloric acid★ 806 parts acetic anhydride	21 to 32	70 to 90	25 to 40 volts 0.1 to 0.15 amp/sq cm	Tin	Several minutes	Stir bath if time ex- ceeds 8 to 10 min.
Titanium	60 parts perchloric acid★ 350 parts butyl cellosolve 590 parts methyl alcohol	24 75		58 to 66 volts 2 to 3 amp/sq cm	Stainless steel	40 sec	Polishes only.
Titanium	90 ml ethyl alcohol 10 ml n-butyl alcohol 6 g aluminum chloride (AlCl_3) (add slowly) 25 g zinc chloride (ZnCl_2)	24 to 30	75 to 85	30 to 60 volts 0.2 to 1.0 amp/sq cm	Stainless steel	1 to 6 min	Agitate solution.
Titanium	80 ml glycerine 5 g barium fluoride 5 ml sulfuric acid (cone)			90 volts 0.4 amp/sq cm	Stainless steel	1 to 2 min	Solution heats up during polishing.
Uranium	5 parts orthophosphoric acid 5 parts ethylene glycol 8 parts ethyl alcohol	21	70	18 to 20 volts 0.01 amp/sq cm	Stainless steel	5 to 15 min	
Uranium	1 part chromic acid (50 g CrO_3 , 60 ml water) 3 parts glacial acetic acid	7 45		80 volts 0.8 to 1.6 amp/sq cm	Stainless steel	5 to 30 sec	Keep bath cool.
Zinc	1 part perchloric acid (20%)★ 4 parts ethyl alcohol (96%)	38 max	100 max	50 volts 0.8 amp/sq cm 100 volts 0.6 amp/sq cm 45 to 60 volts 2 to 3 amp/sq cm 20 to 45 volts 1.2 to 1.9 amp/sq cm 35 to 60 volts 1 to 2 amp/sq cm	Stainless steel Stainless steel Stainless steel Stainless steel	10 sec 30 sec and 10-sec intervals 10 sec 10 sec 10 sec	For pure Zn (99.99%). For crude Zn with 2% Pb, 1% Sn and 0.2% Fe. For 1.6 and 4% Cu alloys. For Zn with 4% Al and 1% Cu. For Zn with 7% Al and 4% Cu.
Zinc	25% solution of potassium hydroxide	24 75		2 to 6 volts 0.16 amp/sq cm	Copper	15 min	Agitate bath with air or nitrogen.
Zinc	185 parts orthophosphoric acid 315 parts ethyl alcohol	24 75		2.5 volts 0.02 amp/sq cm	Nickel or stainless steel	30 min	

*DANGEROUS. Before mixing or using this reagent, read the precautions given in box on page 169.

Table II. Recommendations for Electrolytic Polishing (continued)

Metal	Bath Composition	Temperature °C °F		Electrical Conditions	Cathode Material	Time	Remarks
Zinc	144 ml ethyl alcohol 10 g AlCl ₃ (anhyd) 45 g ZnCl ₂ (anhyd) 32 ml water 16 ml n-butyl alcohol	10 to 15 50 to 58		25 to 40 volts 0.02 to 0.5 amp	Stainless steel	0.5 to 3 min	For high-purity Zn. Solution slowly agitated.
Zirconium	1 part perchloric acid (60%)★ 10 parts glacial acetic acid	24	75	12 to 18 volts 0.02 to 0.5 amp	Stainless steel	45 sec	Rinse in mild acetic acid solution.
Zirconium	6 parts perchloric acid★ 35 parts butyl cellosolve 59 parts methyl alcohol	24	75	70 to 75 volts 2.5 to 3.5 amp/sq cm	Stainless steel	15 sec	Polishes and etches simultaneously.
Zirconium	2 parts hydrofluoric acid 1 part nitric acid 20 parts glycerine	24	75	9 to 12 volts	Stainless steel	1 to 10 min	Serves as both pol- ish and etch.

*DANGEROUS. Before mixing or using this reagent, read the precautions given in box on page 169.

Table III. Recommendations for Electrolytic Etching

Metal	Bath Composition	Temperature °C °F	Electrical Conditions	Cathode Material	Time	Remarks
Aluminum	49 parts methyl alcohol 49 parts distilled water 2 parts hydrofluoric acid	<24 <75	30 volts	Aluminum	1 to 2 min	Produces grain con- trast with polar- ized light.
Aluminum	70 parts orthophosphoric acid 2.5 parts distilled water 26.5 parts carbital 1 part hydrofluoric acid	20 68	50 volts	Carbon	5 to 20 min	Produces grain con- trast with polar- ized light.
Aluminum	100 g citric acid 3 ml hydrochloric acid 20 ml ethyl alcohol Water to make 1 liter	24 75	12 volts 0.2 amp/sq cm	Carbon	1 min	For duralumin-type cast alloys.
Aluminum	210 parts orthophosphoric acid 45 parts amyl alcohol 65 parts distilled water	24 75	0.75 to 1.2 amp/sq cm	Stainless steel	1.5 to 2.5 min	For 2S & 3S Al.
Beryllium	Fuming nitric acid	24 75	18 volts	Stainless steel	20 to 40 sec	
Brass	3 parts orthophosphoric acid 5 parts water	16 to 27 60 to 80	0.01 amp/sq cm	Copper	Few seconds	Alpha and beta brass.
Brass	4 parts orthophosphoric acid 6 parts water	24 75	0.008 to 0.012 amp/sq cm	Copper	Few seconds	Alpha brass.
Bronze	67 parts orthophosphoric acid 10 parts sulfuric acid (conc) 23 parts distilled water	24 75	0.8 volt	Copper	30 sec	For bronze contain- ing up to 6% Sn.
Bronze	47 parts orthophosphoric acid 20 parts sulfuric acid (conc) 33 parts distilled water	24 75	0.8 volt	Copper	30 sec	For bronze contain- ing more than 6% Sn.
Cobalt	Orthophosphoric acid	24 75	1.2 volts	Stainless steel	Few seconds	Agitate bath.
Cobalt and Alloys	5 parts hydrochloric acid 1 to 10 parts chromic acid (10%)	24 75	6 volts	Platinum or stain- less steel	10 sec	Cathode distance, 3/4 to 1 in.
Cobalt and Alloys	10 g chromic oxide (CrO ₃) 90 ml water	24 75	6 volts	Platinum or stain- less steel	10 sec	Cathode distance, 3/4 to 1 in.
Cobalt Alloys	5 to 10% hydrochloric acid	24 75	3 volts	Carbon	1 to 5 sec	
Copper	2 parts orthophosphoric acid 1 part distilled water	24 75	0.8 volt	Copper	30 sec	Suitable for alloys except tin bronzes.
Copper	30 g ferrous sulfate 4 g sodium hydroxide 100 ml sulfuric acid 1900 ml water	24 75	8 to 10 volts 0.1 amp		15 sec	Darkens beta in brass.
Germanium	Oxalic acid (100 g/l water)	24 75	4 to 6 volts		10 to 20 sec	Grain boundary etch.
Gold Alloys	Potassium cyanide (5%)	24 75	5 volts 0.02 amp/sq cm	Stainless steel	20 to 60 sec	
Molyb- denum	Oxalic acid (0.5%)	52 125	3 to 9 volts	Stainless steel	5 sec	

*DANGEROUS. Before mixing or using this reagent, read the precautions given in box on page 169.

Table III. Recommendations for Electrolytic Etching (continued)

Metal	Bath Composition	Temperature °C °F		Electrical Conditions	Cathode Material	Time	Remarks
Molybdenum	Sodium hydroxide (10%)	24 75		1.5 to 3 volts	Platinum or stainless steel	1 to 5 sec	
Nickel and Alloys	Chromic acid (10%)	24 75		1.5 volts	Platinum or stainless steel	1 to 3 sec	
Nickel and Alloys	2 parts nitric acid (conc) 1 part glacial acetic acid 17 parts water	24 75		1.5 volts		20 to 60 sec	Good for nickel alloys. Excellent for grain size.
Nickel and Alloys	Oxalic acid (10%)	24 75		1.5 to 6 volts	Platinum	15 to 30 sec	Good for Inconel.
Nickel and Alloys	Sulfuric acid (3%)	24 75		6 volts		5 to 30 sec	Shows carbides and grain boundaries. Inconel and nickel-chromium alloys.
Platinum	Sodium cyanide (10%)	24 75		6 volts		2 to 5 min	General use.
Silver Alloys	Citric acid (10%) plus few drops nitric acid	24 75		6 volts 0.01 amp/sq cm	Stainless steel	15 sec	General use.
Steel	2 g picric acid 25 g sodium hydroxide 100 ml distilled water	24 75		6 volts	Stainless steel	30 sec	Low-alloy steel. Stains iron carbides.
Steel	Chromic acid (10%)	24 75		3 volts	Stainless steel	Variable	Austenitic or ferritic stainless. Attacks carbides and sigma.
Steel	Sodium cyanide (10%)	24 75		3 volts	Stainless steel	Variable	Outlines euh phase in molybdenum steels.
Steel	Oxalic acid (10%)	24 75		3 volts	Stainless steel	Variable	
Steel	1 part nitric acid 1 part glycerine 3 parts hydrochloric acid	24 75		3 to 6 volts	Stainless steel or carbon	10 sec	Stainless (16-25-6). Etches austenite.
Steel	1 part nitric acid 1 part water	24 75		1.5 volts	Stainless steel	Up to 2 min	Austenitic or ferritic stainless. Etches grain boundaries.
Steel	1 part hydrochloric acid 10 parts methyl alcohol	24 75		230 volts 1.5 amp/sq cm	Stainless steel	1 to 2 sec	Ferritic and martensitic grain-size etch.
Steel	1 part sulfuric acid 19 parts water	24 75		6 volts 0.1 to 0.5 amp	Stainless steel	5 to 15 sec	For Fe-Cr-Ni alloys.
Steel	Ammonium persulfate (10 to 100 g/l water)	24 75		6 volts 0.1 to 0.5 amp	Stainless steel		Attacks carbide, ferrite and austenite in that order.
Steel	Sodium hydroxide (400 g/l water)	24 75		1.5 to 2 volts	Stainless steel		Colors sigma and carbides but not ferrite.
Steel	50 g ammonium molybdate 100 ml hydrochloric acid 75 ml nitric acid Water to make 1 liter	24 75		12 volts 0.3 amp/sq cm	Carbon	2 to 3 min	For 18-8, Nichrome and high-nickel alloys.
Tantalum	Sodium hydroxide (10 g/l water)	24 75		6 volts		3 to 10 sec	General etch.
Thorium	1 part perchloric acid★ 15 parts water	24 75		35 volts	Stainless steel		
Tin	5 parts perchloric acid★ 13 parts glacial acetic acid	21 to 32	70 to 90	15 volts 0.03 to 0.06 amp/sq cm	Tin	100 to 200 sec	Bath not stirred.
Tungsten	Sodium hydroxide (10%)	24 75		1.5 to 3 volts	Platinum or stainless steel	1 to 5 sec	For tungsten and tungsten carbides.
Uranium	4 parts citric acid 1 part nitric acid 195 parts water	24 75		0.01 amp/sq cm	Stainless steel	10 min	Outlines grain boundaries.
Uranium	1 part chromic acid 10 parts glacial acetic acid	49 120		0.8 to 1.2 amp/sq cm	Stainless steel	1 to 3 min	Outlines grain boundaries.
Vanadium	1 part hydrochloric acid 9 parts water	24 75		3 to 6 volts	Stainless steel	Few seconds	
Zinc	5 to 7 parts perchloric acid★ 13 to 15 parts glacial acetic acid	24 75		0.01 amp/sq cm	Copper	Few seconds	
Zinc	1 part chromic acid 5 parts water	24 75		12 volts 1 amp/sq cm	Platinum	10 sec	Differentiates gamma and epsilon in Cu-Zn alloys.

*DANGEROUS. Before mixing or using this reagent, read the precautions given in box on page 169.



Fig. 10. Interface Area Between Cobalt-Base Hard Facing Alloy and Type 304 Stainless Steel (bottom). Cathodically vacuum etched 3 min in argon at 50 microns pressure, 4300 volts, and current density 3.5 milliamperes per sq cm.

to form films of metal on an appropriate base, as in the coating of mirrors. The removal of metal from the cathode surface is not completely random but is related to the microstructure of the cathode; when examined microscopically, the etched surface is similar in appearance to that produced by chemical or electrochemical etching. This application of sputtering to the development of macrostructures and microstructures of metallographic specimens is called cathodic vacuum etching.

The glow discharge is established by applying a high potential between two electrodes (one of which is the specimen) in a partial vacuum. Such a discharge can be maintained under various conditions of pressure, types of residual gas, electrode dimensions and temperature, as well as electrical potential, current and rectification.

Early experimenters encountered various technical difficulties and etched-surface artifacts on specimens so etched. Under some conditions the optical contrast of the resulting microstructure depended entirely on preferential staining that occurred concurrent with etching. In 1949, D. M. McCutcheon revived interest in the method with his work on flowline macrostructures. Today, a variety of metals and alloys can be cathodically vacuum etched to equal or exceed the quality of etching produced by chemical or electrochemical means. The method can produce well defined, stain-free structures in which inclusions are preserved and interfaces are clearly revealed, despite diversities in chemical activity of the structural components. Dissimilar metal couples, which are among the most difficult specimens to etch by conventional methods, can be etched satisfactorily, as shown in Fig. 10. However, the technique is limited in this application by the relative etching rates of the two metals comprising the couple.

The probability of success with any particular metallic couple can be estimated from the relative sputtering rates, as given in the book by J. Strong

cited in the list of references on page 177. For example, silver-cadmium alloys coupled with steel, and zinc coupled with iron, do not respond satisfactorily to cathodic vacuum etching because of the great differences in sputtering rates between the components. Tolerable differences in rate are found to exist in couples of steel with cupro-nickel, steel with cobalt-base alloys, and others.

The contrast of cathodically vacuum etched structures is generally satisfactory for bright-field examination. However, those structures that derive contrast through preferential staining when etched chemically do not display vivid contrast when etched cathodically unless some staining occurs during the etching process. The fact that stain-free surfaces can be secured is not always advantageous in optical metallography, but is of particular assistance to the electron metallographer in securing high-quality replicas of such etched surfaces.

The process of cathodic vacuum etching is inefficient with respect to metal removal, since some of the incident energy is expended in heating the specimen undergoing bombardment. At times, the temperature of the specimen may be raised high enough to alter the specimen structure radically, particularly on the etched surface. This situation, however, can be prevented by means of a heat sink, as illustrated in Fig. 11, or by a recirculating coolant system to the specimen supporting fixture.

The equipment for cathodic vacuum etching may be obtained commercially, or the basic components (such as a high-voltage source, diffusion pump, mechanical vacuum pumps, vacuum enclosure, etc.) assembled to meet specific laboratory requirements. Good results have been secured in the use of units designed around conventional evaporators of the type used for shadowing replicas for electron microscope work. In the operation of such equipment, numerous variables of the process must be considered, and the operating conditions properly chosen to produce true

metallographic structures free from artifacts that may arise from redeposition of sputtered metal.

In the use of equipment that provides for cooling of the specimen, a single set of electrical and pressure conditions in a system of fixed geometry (Fig. 11) is generally satisfactory for etching a variety of metals of different shapes and sizes. This includes zirconium, uranium, nickel, aluminum, copper, stainless steel, copper-nickel alloys and others.

The establishment of the above conditions facilitates the use of high ion current densities, and etching time is the controlling variable. With efficient cooling of the cathode specimen, etching times of 1 to 3 min are usually sufficient. With inefficient cooling and lower ion current densities, the time may be extended to 1 to 3 hr. Specimens to be etched for replication, as in electron microscopy, generally require about 50% longer etching times.

Through development of the process, the time and care formerly required to etch a specimen have been greatly reduced. Although suitable for most metals, the process is not a substitute for more conventional etching methods; rather, it is of value for etching those metals, alloys and metallic couples that do not respond satisfactorily to chemical or electrochemical etching procedures.

Electron Metallography

Two types of instruments that produce enlarged images with an electron beam can be applied to metallography. In one, the emission electron microscope, image contrast results from variations in intensity of electron emission from a heated sample. In the other, the transmission electron microscope, image contrast is caused by variations in the transparency of the sample or a replica of it to an electron beam.

The emission electron microscope is still in a very early stage of development with perhaps no more than half a dozen instruments in existence. (Description of the emission microscope and discussion of its potential usefulness.

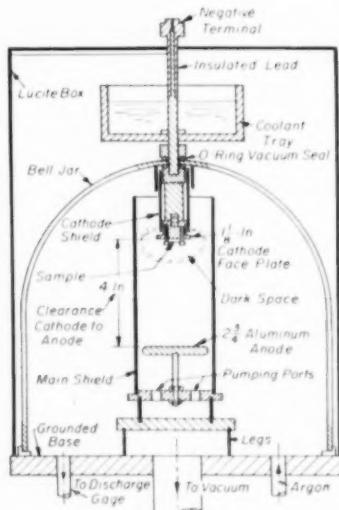


Fig. 11. General Arrangement of Components for Cathodic Vacuum Etching in a Bell Jar

ness in metallography can be found in many of the references on electron metallography cited on page 177.) Transmission electron microscopes are available commercially, and hundreds of them are now being used in metallography. The discussion that follows deals with the available type.

The Electron Microscope. The optical similarities between light and electron transmission microscopes are shown in Fig. 12. Each component of the light microscope—source, condenser lens, objective lens, projecting eyepiece and ground viewing glass—has a corresponding component in the electron microscope. Source of the electron beam is an electron gun consisting of a tungsten hairpin filament and shield, maintained at some high negative voltage, and a grounded anode ring. The heated filament emits electrons which are accelerated through the anode opening and pass down the column of the microscope as a "monochromatic" electron beam. The column of the electron microscope must be evacuated by pumps to a vacuum of 0.05 micron to prevent dispersion of the electron stream by collisions with gas molecules. A voltage of 50,000 accelerates the electrons to about half the velocity of light so that the beam has a wavelength of 0.05 Å, about 1/100,000 that of the green light frequently used in optical metallography.

The lenses are specially shaped electric or magnetic fields which focus the electron beam and produce an image, just as properly shaped glass focuses light rays. At present most electron microscopes are of the electromagnetic type; that is, the lenses are magnetic fields generated by solenoidal coils conducting direct current. The strength of the magnetic field and thus the focal length of the lens can be varied by changing the current in the lens coil so that control of the cone of illumination (hence control of the intensity), sharp focusing of the image, and selection of the magnification are all accomplished by adjusting the power

supplied to the condenser, objective and projector lenses, respectively.

Focal lengths of 2 to 4 mm and magnifications of 100 to 200 diameters make the objective lenses of electron microscopes comparable to the high-power objectives of light microscopes. A variable projector lens projects the image, further enlarged, on a viewing screen coated with phosphor, which fluoresces under bombardment by the electron beam. Direct instrument magnification can be varied from as low as 1000 up to 20,000 diameters (some models go as high as 80,000). Micrographs are made by permitting the electron beam to fall directly on an ordinary photographic emulsion either by drawing the viewing screen aside or by moving the plate or film into the beam above the screen. In printing, the record can be enlarged up to 8 times for a maximum useful magnification of 150,000 diameters.

The relative intensity (brightness of viewing screen or darkening of photographic plate) at any point in the final image depends mainly on the scattering power of the corresponding point in the specimen. This scattering power is the product of the local density and thickness and determines the percentage of the electrons that are sufficiently deflected in passing through the specimens to be intercepted by the aperture stops. Metal specimens thicker than 0.02 to 0.05 microns are opaque to the electron beam and therefore most metal structures must be examined by replica techniques, as described in a following section.

Because of the severe spherical aberration of electron lenses, small apertures must be used to eliminate all but paraxial rays. For this reason, the numerical aperture of the objective is only about 0.002, and the great potential improvement in resolution over the light microscope, because of the very short wavelength of the electron beam, is reduced considerably. The actual resolution of the electron microscope is about 100 times that of the light microscope but the necessity of using replicas

reduces the resolution gain to about 50 times for metal samples.

The small numerical aperture of the objective results in great depth of field and focus; thus, the entire field of an electron micrograph will be in sharp focus, including any peaks and valleys on the specimen, so that electron stereomicrographs are possible.

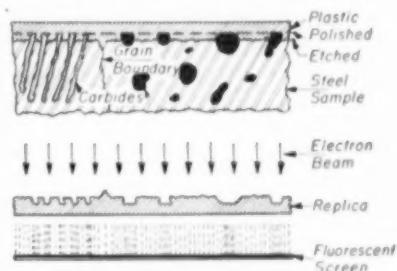


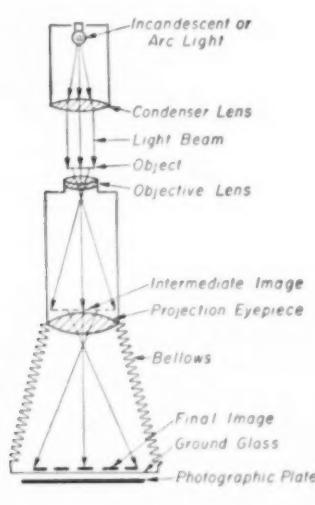
Fig. 13. Schematic Representation of Negative Plastic Replica Technique

Replica Techniques. Restriction to extremely thin specimens necessitates the use of thin replicas in electron metallography. Replica methods fall into three general classifications: (1) those that derive their contrast from the surface relief resulting from differential etching of the components of the microstructure after polishing; (2) those deriving their contrast from differential chemical activity (such as rate of oxide formation) of the components of the microstructure, and (3) a relatively new type of replica for studying fine precipitates that gets its contrast from the electron scattering power of the precipitate particles themselves. Detailed descriptions of the various replica methods can be found in the references to ASM and ASTM publications in the list on page 177.

The sample surface is usually prepared about as for light micrography at highest magnification (3000 \times). Because of the shallow etch, flowed metal must be carefully removed from the sample by alternate polishing and etching. Electrolytic polishing and etching are frequently employed for soft metals in order to avoid smearing. The sample must be well rinsed with alcohol to remove all trace of etching stain from the surface.

Surface Relief Replicas. Thin films or replicas with variations in transparency to the electron beam corresponding to variations of surface relief of the sample can be prepared in several ways. The negative plastic replica method is one of the most frequently used (Fig. 13). A dilute solution of plastic is flowed over the polished and etched surface and allowed to dry to a thin film. When dry and stripped from the sample, one side of the plastic film carries a reverse impression of the surface, resulting in variations in thickness or electron scattering power which give rise to contrast in the final image.

The contrast of a plastic replica is inherently low but can be enhanced by spraying or "shadowing" the replica surface with a thin film of chromium, uranium, platinum, or other metal by thermal evaporation in a vacuum system. Figure 14 shows a negative plastic replica, shadowed with uranium, of a sample of 0.81% C steel quenched before the completion of isothermal



Light Microscope

Electron Microscope

Fig. 12. Schematic Comparison of Light and Electron Transmission Microscopes

transformation to pearlite at 1250 F. The interlamellar spacing of the very finest pearlite that formed during the rapid cooling is less than 0.02 microns which is about 1/10 the limit of resolution of the light microscope.

Shadowed plastic replicas are the easiest to prepare and do not damage the sample surface, so that a number of replicas can be made of the same prepared surface. Electron micrographs of shadowed replicas usually correlate well with the appearance of microstructures in the optical microscope.

If silica, beryllium, germanium or some other material of low electron scattering power is used for shadowing, the shadow film can be made thick enough to be self-supporting and yet be transparent to the electron beam. Thus, a heavy plastic replica of the sample surface can be dissolved away after vacuum metallizing and only the metal or metal oxide replica examined in the electron microscope. Figure 15 shows a silica replica of coarse pearlite formed isothermally in a eutectoid carbon steel. Replicas of this type have great stability in the electron beam and are useful for stereographic studies of samples with considerable relief, such as fracture surfaces or deeply etched structures.

Replica granularity caused by the molecular structure of the plastic can be avoided by eliminating the initial plastic impression by spraying the shadowing material directly onto the sample surface. Thick metal or metal oxide replicas made this way usually can be removed from the surface only by dissolving the metal sample from beneath the replica so that the replica floats free. Thin metal films of chromium or platinum can be stripped by first depositing a monomolecular layer of a wetting agent such as boron oxide or sodium octyl as a parting layer before shadowing. The thin metal replica must be backed with a thin film of plastic to support it during stripping and during examination in the electron microscope. These preshadowed plastic

replicas are excellent for surfaces with fine detail but little relief.

Surface Film Replicas. The three general steps of this replica method are: (1) surface preparation; (2) development of a suitable surface film, and (3) stripping of this film. Although several types of surface films could be used for this technique, only surface oxide formation has been employed to the present time. Oxide replicas have proved useful for examining the subgrain structure of aluminum, and the microstructures of stainless steels, nickel alloys and alnico magnetic alloys where it is difficult to develop sufficient differential relief for the surface relief type of replica.

The surface is first prepared for film formation either by electrolytic polishing or by mechanical polishing plus light chemical etching to remove any film of disturbed metal. A surface oxide film may be formed in several different ways, depending on the sample. For stainless steels, nickel and nickel alloys, the oxide film is usually developed thermally by some form of heat tinting. A hot oxidizing flame played over the surface for several seconds, or immersion of the sample in a hot oxidizing agent such as molten $\text{NaNO}_3\text{-KNO}_3$ at 500 C for a few seconds, is usually sufficient to develop an oxide film 150 to 200 Å thick, which will appear as a golden or straw-colored temper film. An excellent surface oxide film can be developed on aluminum and aluminum alloys by a special anodizing treatment, which will produce an almost structureless aluminum oxide film about 200 Å thick.

The surface films are stripped by dissolving the underlying metal. First, the surface is scribed into a grid of $\frac{1}{8}$ -in. squares by scratching through the oxide film with a sharp needle, and then the sample is immersed in an alcoholic solution of iodine or bromine if it is a stainless steel or nickel alloy, or into concentrated mercuric chloride if it is an aluminum alloy. Stripping solutions attack the interface between the sur-

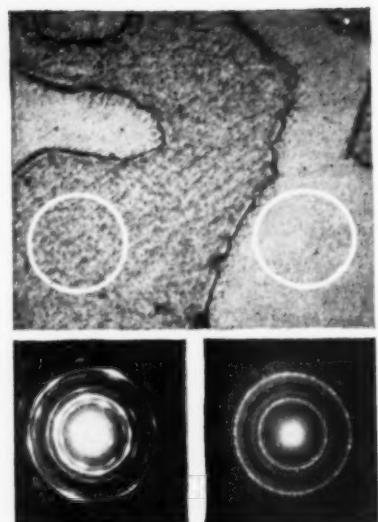


Fig. 16. Surface Oxide Replica of 25% Cr, 20% Ni Steel Aged at 1200 F to Form Sigma (FeCr) Phase. Electron diffraction patterns identify oxide films as Cr_2O_3 over sigma phase and $\text{NiO}\cdot\text{Fe}_2\text{O}_3$ over ferrite. 10,000 \times

face oxide and the metal rapidly so that the replica films will float free after a few minutes. The small squares are caught on small disks of fine-mesh screen and are rinsed in distilled water and in alcohol before drying.

Figure 16 shows an oxide replica of sigma phase (FeCr, a hard, brittle, intermetallic compound) which formed in a sample of 25 Cr - 20 Ni steel during aging at 1200 F. The lighter areas showing a thin oxide film correspond to areas of the slower scaling chromium-rich (FeCr) precipitate. The oxide film formed over the chromium-poor ferrite is thicker and made up of much larger crystallites. The electron diffraction patterns from the marked areas indi-



Fig. 14. Shadowed Plastic Replica of 0.81% C Steel Partly Transformed to Coarse Pearlite and Quenched. 19,000 \times



Fig. 15. Silica Replica of Coarse Pearlite in 0.87% C Steel Formed Isothermally at 1300 F. 13,000 \times

cate the formation of large oriented crystals of $\text{NiO} \cdot \text{Fe}_2\text{O}_3$ over the ferrite and of small randomly oriented crystals of Cr_2O_3 over the sigma particles during oxidation to develop the surface film replica.

Extraction Replicas. This type of replica gets its name from the fact that the particles are actually removed from the surface by the replica. The first steps of this replica technique are the same as for shadowed plastic replicas, as shown in Fig. 17. After polishing and etching, a thin film of plastic is formed over the surface by drying from dilute solution, but instead of being stripped at this point, as with the shadowed plastic method, the sample is etched again through the plastic film. Etching solutions diffuse through the plastic and etch the sample almost as rapidly as before the plastic was applied. As can be seen from the sketch, the particles partially embedded in the plastic are removed with the replica if the second etch is deep enough to free them from the parent metal.

Although this method has been applied mainly to carbon and alloy steels it is suitable for the study of fine precipitates in other alloys. The essential requirement is the availability of an etchant capable of dissolving the metal but not the precipitate particle and also not disintegrating the plastic. Most of the alcoholic etching solutions of ferrous metallography are suitable.

Extraction replicas have greater inherent resolution than other replicas because the fine precipitate particles

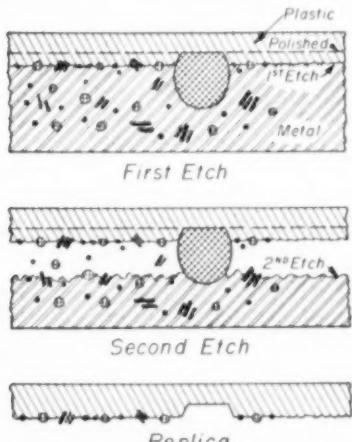


Fig. 17. Schematic Representation of Extraction Replica Technique

themselves are examined rather than a replica copy of them. Another advantage is that the actual precipitate particles present on the replica can be identified by electron diffraction from selected areas.

Figure 18 shows an extraction replica of carbides formed in a 3.2% Mo steel during cooling. Electron diffraction patterns (not shown) revealed both the rod-shaped and the cube-shaped particles to be Mo_2C .

Range of Use. The electron microscope has become more useful for examining structures too fine to be adequately resolved by the optical microscope, chiefly because of recent improvements in the techniques of electron metallography, but also as a re-

sult of better understanding of the type of problem where the method is likely to prove useful.

In addition to clarification of optically irresolvable structures, the electron microscope is used for quantitative measurements of grain size, undissolved carbides, retained austenite and other

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INDEX*

A

Abrasive cleaning of	
steel sheet	134
titanium and its alloys	83
Acetic anhydride, hazards with	169
Acid cleaning	131-134
Adhesive bonding of magnesium alloys	74
Admiralty metal	64-67
Agitation of quenching mediums	A1-126-127
Air-hardening tool steels	22, 24, 28-31
AISI-SAE classification, steel	3, 7, 16 to 20F
AISI-SAE classification, tool steels	21, 22
AISI Steel Products Manuals, Index	140
Alkaline cleaning	131-134
Alloy irons	
composition ranges (T)	92
piston ring application (T)	92, 93
press tool application	30
Alloy steels. See also Steel	
carbonitriding	126
case hardenability of	13
composition (T)	20F
H-steels (T)	16-20E
core hardness range (2% alloy)	14
fatigue limit	1, 2, 101-103, 105, 106, 119
gear applications	13, 14
hardenability	4, 6, 10, 11
hardenability bands (T)	16-20E
hardness vs tempering temp (P)	12
machinability	13, 141-150
notch sensitivity	101, 102
plant standardization, problem (T)	15
selection (A)	1-20
cost basis (T)	11
engineering considerations	1
hardenability (T)	11, 16-20E
tensile properties (P)	12
Almen test strips (P)	106
Aluminum	
applications (A)	52-63
consumption 1920-1953 (P) (T)	52
electrolytic etching (T)	172
electrolytic polishing (T)	170
high purity, reflectivity applications	60
Aluminum alloy castings, production	53
properties (T)	62, 63
Aluminum alloy forgings, properties, transverse and longitudinal (P) (T)	54, 55
Aluminum alloy pistons, properties and applications	55, 94
Aluminum alloys, aircraft applications	53-55
anodized and clad surfaces	53, 54
anodized oxide film	176
anodizing colors	58
applications (A)	52-60
automotive applications	55, 56
bearing application	56
brazability	58
building applications, bibliography	59
cathodic protection of	77
chemical applications	59
construction applications	58, 59
corrosion in fuming nitric acid (T)	53
corrosion resistance	53-54, 59
damping capacity	58
die steels for	33
electrical applications	57, 58
elevated-temperature properties	53
extrusion presses	54, 55
finishes on electrical appliances	58
forgings	54, 55
furniture applications	58
galvanic corrosion	57
hand forgings (T)	54
instrument applications	60
irrigation pipes	60
jigs and fixtures	60
marine applications	56, 57
materials handling applications	59, 60
mining machinery applications	60
notch sensitivity factor (P)	101, 102
paper industry application	60
piston applications	55, 94
portable tool applications	60
prestressing extruded	109
production	52
properties, data sheets	60-62
properties of new alloys	63
railroad applications	56
reflectivity applications	60
rivet applications	54
standard alloy designations (T)	73
strength-weight ratio application	60
stress-rupture (P)	48
textile machine applications	60
welding	54

*Compiled by Evelyn H. Roberts, Cleveland

The letter (T) or (P) in parentheses after an index entry means that the information referred to is in a Table or Figure, respectively, on one of the pages mentioned. The letter (A) means that the topic is the subject of an article.

Aluminum alloys, trade designations	
A178, composition and properties	63
Cond-Al	57, 58
Duralumin, effect of shot peening on fatigue strength (T)	107
EC Alloy	57
14S-T6, forged part, properties transverse and longitudinal (T) (P)	54, 55
hand forgings, specifications (T)	54
4S, properties	60, 61
B18S, composition and properties	63
F18S, properties	63
24S-T3, effect of temperature on properties (P)	53
24S-T4, strength-weight ratio with temperature (P)	53
50S, properties	61
A50S, composition and properties	63
J51S, composition and properties	63
53S-T61, corrosion resistance	63
A54S, composition and properties	63
55S, clad, composition and properties	63
C57S, anodizing characteristics	63
C57S, composition and properties	63
61S, composition and properties of clad	63
61S-T4, welding of	63
61S-T6, specifications reference	63
62S, composition and properties	63
63S, properties	61
75S-T6, aircraft parts formed by peening	107
75S-T6, effect of temperature (P)	53
75S-T6, hand forging specifications (T)	54
75S-T6, strength-weight ratio with temperature (P)	53
D132, composition range (T)	86
piston applications (T)	92
138 alloy, properties	62
B214, properties	62
F214, composition and properties	63
R305, composition and properties	63
Ternally	63
Aluminum bearings	56
Aluminum brass, composition (T)	65
Aluminum brass, inhibited, condenser tubing application	
corrosion resistance to waters	64
Aluminum bronze, wrought, arc welding	
cold forming after welding	67
compositions (T)	65
conductivity of wrought (T)	66
corrosion resistance	67
de-aluminification	67
gas-shielded metal-arc welding	67
hot forming after welding	67
joining characteristics	66
mechanical properties	64, 66
tarnishing	66
tensile strength (T)	66
use at high temperature	64
valve guide application	95
welding rod application	67
Aluminum bronze castings, applications	72
castability rating (T)	68
casting difficulties	70
composition	69
composition for castings (T)	68, 69
corrosion resistance	70-72
effect of aging on heat treated	71
effect of aluminum on properties	70, 71
effect of iron on properties	70
effect of nickel on properties	71
effect of slow cooling on properties	71
fatigue limit	71
fluidity ratings (T)	68
heat treatment	70
joining characteristics (T)	71
permanent mold casting	68
plaster mold casting	68
properties of castings (T)	70
strength with cross section	71
Aluminum-copper-magnesium	
Al - 2.6 Cu - 0.35 Mg, composition and properties	63
Aluminum-copper-magnesium-nickel	
Al - 2.0 Cu - 1.5 Mg - 1.0 Ni, properties	63
Aluminum-copper-nickel-magnesium	
Al - 4.0 Cu - 2.0 Ni - 1.5 Mg, composition and properties	63
Aluminum-copper-silicon-magnesium	
Al - 10.0 Cu - 4.0 Si - 0.3 Mg	62
Aluminum forgings, properties, transverse and longitudinal (P), (T)	54, 55
Aluminum investment castings, production	53
Aluminum-magnesium alloys	
Al - 0.8 Mg, composition and properties	63
Al - 1.2 Mg, properties	61
application in welding	57
Aluminum-magnesium-chromium	
Al - 3.5 Mg - 0.25 Cr, composition and properties	63
Aluminum-magnesium-manganese	
Al - 1.0 Mg - 0.3 Mn, composition and properties	63
Al - 4.5 Mg - 0.5 Mn, clad, composition and properties	63
Aluminum-magnesium-silicon	
Al - 0.7 Mg - 0.4 Si, properties	61
Al - 3.8 Mg - 1.8 Si, properties	62
Al - 4.0 Mg - 0.5 Si, composition and properties	63
Aluminum-magnesium-silicon-copper	
Al - 0.6 Mg - 0.35 Si - 0.25 Cu, composition and properties	63
Aluminum-magnesium-silicon-copper-chromium	
Al - 1.0 Mg - 0.6 Si - 0.25 Cu - 0.1 Cr, composition and properties	63
Al - 1.0 Mg - 0.6 Si - 0.25 Cu - 0.25 Cr, clad, composition and properties	63
Aluminum-manganese-magnesium	
Al - 1.2 Mn - 1.0 Mg, properties	60, 61
Aluminum-silicon brazing alloy	
Al - 9 Si - 3.5 Cu - 0.8 Ni	62
Aluminum-silicon bronze	
Al - 6.5 Zn - 0.7 Mg - 0.5 Cu, composition and properties	63
Aluminum-silicon-copper-iron	
Al - 9.7 Si - 2.3 Cu - 0.6 Fe, marine application	57
Aluminum-silicon-copper-magnesium-nickel	
Al - 9 Si - 3.5 Cu - 0.8 Ni	62
Aluminum-zinc-magnesium-copper	
Al - 6.5 Zn - 0.7 Mg - 0.5 Cu, composition and properties	63
Ammonia atmospheres (T)	130B
Ammonia for carbonitriding	124, 125
Anodizing of	
aluminum assemblies	56
electrodes	58
Architectural bronze	65
Arc melting of titanium	80
Arc welding, see Welding, metal concerned	
Atmospheres for carbonitriding	124, 125
Atmospheres for heat treating	130B
Austenitic alloys, high-temperature behavior	42
Autopour in steel making	156, 157

B

Bearing area analysis	95
Bearing loads, bronze	71, 96
Bearing loads, engines	93, 96
Bearing properties	71, 96
Bearings,	
aluminum	56
aluminum-cadmium-silicon	56
bronzes (T)	96
composite	56, 96
copper alloy castings	71
engine	95, 96
porous bronze or iron	151-153
Beryllium copper, composition (T)	65, 69
fatigue limits (T, footnote)	66
fatigue strength, applications	64
joining characteristics (T)	71
properties of castings (T)	70
Bessemer process	154
Blanking, definition	28, 136
Blanking dies	28, 136
Blanking of	
steel sheet	136
tinplate	81
Blast cleaning	133, 134
Boiler code stresses (T)	42
Bolt steels, alloys for	45
properties (T)	42
service temperatures for	45
Brass,	
See also Copper alloys, Copper alloy castings	
compositions (T)	65
conductivity (T)	66
corrosion	67
dezincification	67
finishing	66
forming	65
machinability (T)	67
tensile strength (T)	66
welding	66, 67
Brazed joint design (A)	115-122
Brazed joints, cemented carbide to steel	117
clearance vs strength	117
corrosion resistance	121
design, illustrations (P)	117
design stress, allowable	120
electrical conductivity	120, 121
fatigue limits	119, 120
fatigue limit in shear (T)	120
fatigue limit vs clearance (T)	120
fatigue strength	119, 120
heat treatment	116, 117
high-temperature service (T) (P)	121
impact strength	120
joint clearances (T)	116
low-temperature service	120

Brazed joints (continued)	
preparation of surfaces	122
replaced filler metal forms (P)	117
properties vs temperature (T)	120, 121
S-N diagrams	119
shear strength summary (P)	118
shear vs temperature	120
soundness of joint	115, 122
strength	117, 118
strength vs clearance	118-120
strength vs temperatures (P)	120, 121
stress concentration (P)	117, 119
stress distribution in wetting and bonding	118, 119
Brazing.	
definition	115
fluxes	122
process and methods	121, 122
Brazing filler metals.	
brazing temperature range (T)	117
classifications, AWS-ASTM (T)	116
compositions (T)	116
liquidus temperature (T)	117
maximum service temperatures (T)	121
selection	116
solidus temperature (T)	117
strength	117, 118
Brazing of	
copper alloys	67, 115-122
powder metal parts	153
steel	118-120
Brazing processes, heating methods	
tabulation (T)	122
Bright field illumination	164
Brittle failures.	
in structural steels	2
tests for	2
Brittle fracture, impact transition (P)	2
Brittleness, definition	100, 101
Broaching.	
cutting fluids for	148
powder metal parts, tool (P)	152
titanium and its alloys	82
Bronze	64-72
See also alloy concerned	
compositions (T)	65
conductivity, wrought (T)	66
cast	72
Bronze bushings.	
corrosion of	98
for engines and machines	71, 95, 96
nondestructive inspection	162
Burnishing tools for powder metal parts (P)	152, 153

C

Cadmium copper.	
comparative conductivity (T)	68
composition (T)	65
Camshafts, engine	94
Carbide tools	21-33, 134-153
Carbides in molybdenum steel, extraction	
replicas of (P)	177
Carbon, combined	110-112
Carbon steel.	
See also High-carbon high-chromium steel, Low-carbon steel, Carbon tool steel	
applications	13, 14
ASTM specifications for castings	114
carbonitrided, for gears	14
carbonitrizing (A)	124-126
compositions (T)	3
hardenability	6, 10, 11, 125, 126
hardness vs strength (P)	12
machinability (T)	13, 146-148
machining (A)	141-151
melting (A)	154-158
photomicrographs (P)	176
plant standardization (T)	15
properties (T), (P)	5, 12
SAE-AISI (T)	3, 5, 22
scaling (P)	39
selection (A)	1-20
standardization of stock (T)	15
tolerances, bars (T)	4
Carbon steel sheet and strip, tolerances (T)	140
Carbon tetrachloride.	
hazards with	134
Carbon tool steel.	
applications	29, 31, 33
classification (T)	21, 23
composition	23
selection	21-32
Carboaluminizing (A)	
applications	14, 125, 126
atmospheres for	124, 130B
case depth	124
case depth factors (P)	125
definition	124
equipment for	124, 126
gases for (T)	125
selection	125, 126
selective case hardening	126
Carburizing.	
cost example	130, 130A
ferrous powder metal parts	153
high speed tool steel	29
selection (P)	125
selective case hardening	126
steel	13
Cartridge brass	65, 66
Case hardening	13, 14, 124-126, 153

Cast iron.	
See also Gray iron and Nodular iron	
applications	30, 51, 92, 94, 109-114
combined carbon	110, 111
compositions (T)	92
machinability (T)	148
machinability and microstructure (P)	145, 146
machining (A)	141-151
wear resistance	92
Castability.	
of cast iron and steel	109-114
of copper alloys (T)	68
Casting, continuous, of steel	157, 158
Castings.	
design of ferrous (A)	109-114
patterns	110
production 1953	109
testing and inspection	110
Cathodic vacuum etching	169, 174
Cemented carbides	21-33, 134-153
Centrifugal casting of copper alloys	68
Chilled iron castings.	
applications	91-96, 111
ASTM specification	111
Chromium copper	64-66
Chromium-molybdenum steel.	
Fe - 1.25 Cr - 0.5 Mo, stress rupture (P)	48
Fe - 5.0 Cr - 0.5 Mo, stress rupture (P)	48
Chromium-molybdenum-vanadium steel.	
creep	45
Chromium-nickel-cobalt-iron alloys, stress rupture (P)	48
Chromium-nickel-iron, heat-treated, stress rupture (P)	48
Chromium plate.	
wear applications	92, 93
Chromizing of powder metal parts	153
Cleaning	
ferrous metals (A)	131-134
magnesium and its alloys	74, 75
titanium and its alloys	83
Cobalt-base alloys (heat-resisting).	
applications	48
compositions (T)	47
impact resistance of cast	45
stress-rupture (T), (P)	48
Cobalt-base cutting tools (cast)	142
Cobalt-nickel-chromium-iron alloys.	
compositions (T)	47
stress-rupture (T)	48
Cobalt tool steel, selection and heat treatment	25
Coining of powder metal parts	152, 153
Cold drawing of steel	4
Cold drawn carbon steel bars.	
properties	4, 12
tolerances	4
Cold drawn steel, yield vs tensile dies	3
Cold extrusion,	
process	139, 140
Cold forming of	
copper and its alloys	65, 87
steel sheet (A)	134-140
titanium	81, 82
Cold heading dies	30, 31
Cold shearing,	
tool steels for (T)	27, 28
Cold shims, detection of	162
Cold trimming, definition, steels for	26
Cold upsetting	65
Commercial bronze	65-66
Commercial G bronze	69-71
Compacts. See also Powder metal parts	
iron, coining vs properties (T)	153
sintered	151-153
Compression forming of steel	139, 140
Constructional steels (A)	1-20F
Continuous casting of steel	157, 158
Copper.	
braze	67
corrosion resistance, cast	72
corrosion resistance, wrought	64, 67
electrical conductivity, cast	72
wrought	64
electrolytic tough pitch (ETP)	64-66
formability, wrought	65
free-cutting (Se, Te and Pb)	64-66
joining, wrought	66
machinability, cast	68
wrought (T)	66
mechanical properties, cast	69
mechanical strength, wrought	64, 66
oxygen-free (OF)	64-66
phosphor-deoxidized (DLP)	64-66
selection of (A)	64-72
shear strength (P)	118
silver-bearing	64-66
softening temperature	64
stress-corrosion cracking	67
surface finish, wrought	66
thermal conductivity, cast	72
wrought	64
Copper (99.85%), properties of casting (T)	72
Copper alloy castings.	
applications	68, 71, 72
compositions (T)	68, 69, 72
corrosion resistance	71
cost, relative (T)	68
fatigue limits	71
joining, wrought	68, 69
machining	68, 69
properties (T)	72
selection of alloy	68

Copper alloys.	
bearing and wear properties, cast	71
braze	67, 121, 122
castability (T)	68
castings	68-72
cold forming of	65
color range	66
composition, castings (T)	72
wrought (T)	65
corrosion resistance (T)	67, 72, 95
electrical conductivity, cast	72
wrought, and (T)	64, 66
embrittlement in	64, 69
enameling on	66
fatigue strength, (T) and (P)	64, 66, 119
finishes for	66
formability, wrought	65
general-purpose alloys, cast	68
hot forming	65
joining, cast	71
wrought	66, 67
machinability (T)	67
cast	68
wrought	66
mechanical properties, cast	64, 66
plating	66
properties, cast	69, 70, 72
relative costs (T)	64, 66, 72
SAE designations,	
68B, bushings	96
791, bushings	96
season cracking	67
selection of (A)	64, 72
service temperature	64
soldering	67
stress corrosion cracking	64
surface finish, wrought	66
thermal conductivity, cast	72
wrought	64
yield strength, definition	64
Copper-aluminum-silicon, Cu - 7 Al - 2 Si.	
tensile strength (T, see footnote)	66
Copper-beryllium-cobalt (T)	72
Copper brazed joints.	
fatigue	119, 120
high-temperature service (P)	121
Copper brazing (A)	115-122
Copper brazing filler metals.	116, 117, 121, 122
compositions (T)	116
maximum service temperatures (T)	121
melting range (T)	117
strength	118-121
Copper-cadmium	65, 66
Copper-chromium, wrought (T's)	66
Copper-chromium-silicon (T)	72
Copper-gold brazing filler metals	116, 117, 122
Copper-nickel alloys	65, 66
Copper-nickel-tellurium	65, 66
Copper plating of magnesium	75
Copper-silicon	72
Copper-tin bearings	71, 96
Copper-tin bronze castings	71
Copper-tin lead	71
Copper-tin-lead-zinc	68, 69
Copper-zinc-nickel	69
Copper-zinc, Cu - 40 Zn, fatigue limit in torsion (P)	119
Copper-zinc brazing filler metals	
116, 117, 121, 122	
Core hardness of steel	13, 14
Core loss tests	160
Corrosion inhibitors for magnesium-dissimilar metal joints	76
titanium and its alloys	84
Corrosion resistance of aluminum alloys	53, 54, 59
aluminum bronzes	70, 72
braze joints	121
bronze bushings	96
copper alloy castings	71
copper alloys (T)	64, 67, 72
engine parts	95, 96
nodular iron	52
stainless steel	39, 41
titanium and its alloys	83, 84
Corrosion-resistant castings	40, 41
Corrosive wear in engines	91
Cost of heat treating (A)	128-130A
Cots.	
copper casting alloys, relative (T)	68
forming sheet steel	135, 136
heat treating (A)	128-130
labor, in heat treating (T)	129, 130
machining	148-150
Couple, bimetallic	57, 67, 176
Cream of	
aluminum alloys (P)	53
heat-resisting alloys	43-44
magnesium alloys (T)	76
titanium	86, 88, 89
V-30 alloy (P)	45
Creep rate and design	46, 47
Cupro-nickel	64-67
Cutter angles for carbide milling (T)	142
Cutting fluids	
removal of	122
types	132, 148
Cutting speeds	
angles	144, 151
Cutting tools.	
life	144
terminology	142, 143
tool steels for	23-25, 142

D

Damping capacity.	46
effect on fatigue strength	46
in designing	85-86
of gray iron	110
Dark field illumination	164
De-aluminification	67, 70, 71
Decarburization,	
stainless steel	156
steel	105
tool steel (T)	24
Deep drawing of sheet steel,	
allowable reduction	138
categories	29, 30
definition	138
illustration (P)	139
ironing	139
lubrication	139
redrawing	138
sequence of operations (P)	139
stress relieving	139
tool steels for	29, 30
Doxidized copper,	
application in heating coils	64
application in tubing	65
application in welding rods	67
cold forming of	65
composition (T)	65
electrical conductivity	66
softening temperature	64
welding	67
Descaling of steel forgings	132, 133
Design engineering,	
damping capacity in	85, 86
surface working of parts	105
Design engineering of,	
brazed joints (A)	115-121
engine parts	94-96
ferrous castings (A)	109-114
stress concentration (A)	97-103
titanium	85, 86
Desincrification of	
copper alloys	67, 72
Dichromate treatment for	
magnesium and its alloys	74
Die block applications (T)	25, 26
Die blocks, pretreated (T)	25
Die casting, tool steel for	33
Die castings applications	55, 58
Die steels. See Tool steels	
Dies,	
cold heading	30
die-casting, tool steels for	33
extrusion	26, 30
for titanium and alloys	80, 81, 82
powder metal coining	153
press	25, 28, 30, 31, 135, 140
thread rolling	31
wire drawing	27
Dimpling of titanium and its alloys	82
Drawing of titanium and its alloys	81
Drawing compounds, removal of	131
Drill rod, brazed joint strength (P)	118
Drilling of	
powder metal parts	152
titanium	82
Dry cyaniding (A)	124-126
Ductile iron. See Nodular iron	
Dye penetrant inspection, of heat-resistant alloys	159, 161, 162

E

Electrical conductivity of	
aluminum	57, 58
brazed joints	120, 121
copper and alloys, cast	72
wrought (T)	64, 66
Electrical conductors, ACSR & EC	57
Electrolytic acid cleaning	131, 132, 134
Electrolytic alkaline cleaning	131-134
Electrolytic etching (T)	169-172, 173
Electrolytic polishing (T)	169, 170-172
Electrolytic tough pitch copper	64-67
Electron metallurgy	174-177
illustrations (P)	176, 177
Electron microscope,	
illustrations of high magnifications (P)	176
range of use	177
schematic diagram (P)	175
techniques	74-77
Electroplating of	
magnesium and its alloys	74, 75
molds for plastics	33
powder metal parts	153
Emulsion cleaning	131, 132
Engine metals and engine wear (A)	91-96
Engines,	
engineering, design	94-96
plated finishes	92-96
selection of metals	92-96
service conditions	91
surface roughness values	92-96
Etching, cathodic vacuum	169, 174
Etching, electrolytic	169, 172, 173
Extrusion, cold, tool steels for	30
presses	54
process for steel	139, 140
section limits, aluminum (T)	55
size limits, aluminum	55
Extrusion, hot, of nonferrous metals, tool steels for	26, 27
Extrusion of titanium, experimental	80

F

Fasteners,	
for magnesium and alloys	76
titanium and alloys for	85
Fatigue,	
definition of terms	51, 97, 100, 108
heat resisting alloys	45
improvement of	2, 97-108, 119, 120
interpretation for steel	1, 2
large diameters, footnote	103
nodular iron	51
relation to size formula	103
shot peening (A)	104-108
steels	1, 2, 97-108
stress concentration (A)	97-103
Fatigue limit data,	
automotive parts	105
interpretation, meaning	1, 2
steels	1, 2, 101-103, 106, 119
torsion	119
Fatigue notch factor, nodular iron	51
Fatigue ratio, nodular iron	51
Fatigue-rupture,	
life tests (F)	44, 45
G 18 B alloy	46
Nimonic 80	45
Fatigue strength,	
aluminum	60-63, 105
brazed joints	119, 120
copper alloys	66, 106, 119
damping and	46
definition	108
effect of decarburization	105
effect of design	97-103
effect of residual surface stress	105
effect of surface	1, 2, 104-108
effect of type of loading	1
experimental model testing	2
magnesium	75, 105
notch sensitivity and	3
vibration and	46
Fatigue strength reduction factor, or	
fatigue notch factor	51, 100, 108
definition	108
Ferrite,	
machining cast iron	145, 146
nodular iron	49, 50, 51
Ferritic alloys, high-temperature behavior	42
Ferritic stainless steels	38-39
Ferritizing annealing of	
nodular iron	49
Ferrous castings, design of (A)	109-114
Filler metal	115
See also <i>Brazing filler metal</i>	
Finishes for	
aluminum alloys	58
copper alloys	66
magnesium	75
piston rings	94
powder metal parts	153
titanium	81, 83
Fluorescent penetrant inspection	159, 161, 162
Forging of	
aluminum (T)	54
brass	65, 67
steel	
shrinkage allowance for die sinking	80
tool steel selection	26
titanium	80, 81, 85
Forging scale removal	132, 133
Forming	
aluminum, by peening	107
copper and its alloys	65, 67
sheet steel (A)	134-140
titanium and its alloys	81, 82
Free-cutting brass	65-67
Free-cutting copper	64-67
Free-cutting phosphor bronze (T)	67
Free-machining steel,	
case hardening of	3, 5
machining (P)	144, 146-148
Furnace and equipment cost in heat treating (T)	129, 130A
Furnace brazing	121, 122

G

Gages,	
for sheet steel	140
tool steel for	31, 32
Galvanic action,	
potential difference between metals	67, 76
Galvanic corrosion of	
aluminum alloys	57
copper and alloys	67
magnesium and its alloys	76
titanium and its alloys	76
Galvanizing of steel, preparation for	133, 134
Gas, in heat treating	124-126, 130B
Gas carburizing of steel, cost	130, 130A
Gas cyaniding (A)	124-126
Gas-shielded tungsten-arc welding	
of copper alloys	67
Gas turbines	43, 85, 86
Gaskets for joining dissimilar metals	76
Gear bronze	69, 71
Gears,	
carbonitriding	14
selection of steels for	13
shot peening	107
tool steels for master gears	32
Gilding metal	65, 66
Grain refinement in magnesium	73

Grain size of copper alloys	65, 66
------------------------------------	--------

Gray iron.

ASTM specifications	111
castability	110
compressive strength	110
damping capacity	110
design	111
dimensional tolerances	111
fatigue improvement	108
finish allowances (T)	111
finish vs wear resistance	93
growth (P)	51
hardness and wear resistance	93
machinability (T)	50, 145-148
microstructure (P)	49, 92, 145
oxidation resistance of class 40	51
specifications	111
trade designations	29, 30, 32
wear resistance	92, 93
Gray iron for	
die-casting dies	33
engines	92-96
tools	29, 30
Grinding of powder metal parts	152
Guerin forming process, for titanium	62
Gun metal	69

H

H-steels,	
austenitizing temperatures (T)	7
composition limits (T)	7
hardenability bands (T)	16-20E
hardness limits specifications (T)	8, 9
heat treating temperature (T)	7
normalizing temperatures (T)	7
selection by hardenability (T)	11
HAE process for magnesium (T)	74
Hardenability of steel,	
as basis of purchase	6
critical section and	10
definition	4
depth of section and C content	10, 11
effect of carbon and alloys on	10, 11
martensite percentage	7
maximum H for min. section	10
measurement of	6
principles	6
relation to cross section	6, 10-13
selection by (T)	11
selection of carbon content	10-12
selection procedure	10
specimen vs round bar	6, 126, 127
Hardening of tool steels (T)	24
Hardened steels, selection (A)	1-20F
Hardening of steel,	
agitation of quenching mediums (A)	126, 127
alloy steel	6, 7, 10-13
carbonitriding (A)	124-126
cost (A)	128-130
hardenability bands	16-20E
tool steels (A)	24-33

Hardness	
case in carbonitriding	125
limits for H-steels (T)	8-9
recommended for tool steels (T)	24
relation of case and core	14

Hastellox alloys. See Heat resisting alloys

Hazards with	
acetic anhydride	169
cleaning solvents and agents	134
heat treating atmospheres (T)	130B
perchloric acid	169
titanium and its alloys	84
Heat resistance of tool steels (T)	24
Heat-resistant brazing filler metals (T) (P)	116, 117, 120-121
Heat-resistant steels for valves	95
Heat-resisting alloys (A)	42-48
bolting applications	45
compositions (T)	47
corrosion resistance	46
creep data of ACl types (T)	46
design stress	45, 47
creep rate and	46
factors influencing	47
for high-temperature usage	45
dynamic loading-rupture (P)	45
elevated-temperature properties (P)	42
elevated-temperature tests for	42-48
fatigue-rupture data (P)	45, 46
high-temperature fatigue tests	45
impact resistance of wrought	45
inspection	162
microstructure	46
oxidation resistance	46
rupture strength (T)	46
sorting	162, 163
stress-creep rate (P)	44
stress-rupture properties (T)	48
stress-temperature data (P)	48
testing	162
Heat-resisting alloys, trade designations,	
347, brazed joints data (P)	121
compositions (T)	47
creep of ACl types (T)	46
ductility (T)	43
fatigue-rupture (P)	46
Inconel X, short time tests	42
strength/wt. vs temp.	86
rupture data (P)	44
stress-deformation tests (P)	44
S-590, brazed joints data (P)	121

Heat treating of	
nodular iron	49, 50
powder metal parts	153
Heat treating of steel,	
agitation of quenching mediums	126, 127
ASM form for cost of	128
ASM short form for cost of	130A
atmospheres (T)	130B
atmospheres, hazards with (T)	130B
conditions for hardening	10
cost of (A)	128-130A
equipment cost in (T)	128, 129, 130A
fixed costs in (T)	128-130
labor costs in (T)	128-130
tempering vs properties	12
variable costs in (T)	128-130
High-carbon high-chromium tool steels	22, 23
High-leaded brass	66-67
High-leaded tin bronze,	
casting of	68, 69
joining (T)	71
properties (T)	70
High speed steel lathe tools,	
application	147-152
selection of tool steel	23
tool life	149
tool life (formula)	144
High speed tool steel,	
choice of grade	24, 25
classification (T)	21, 22
compositions (T)	22
molybdenum vs tungsten	25
pack carburizing	29
production of Mo and W (F)	25
selection	24, 25
tungsten vs molybdenum	25
High speed tool steels for	
blanking and piercing dies	28, 29
cutting tools	23
extrusion, hot and cold	26, 30
milling titanium	82
plastics molds	33
severe service dies	30
thread-rolling dies	31
trimming, hot and cold	26
High-strength cast manganese bronze	69-71
High-strength cast yellow brass	69-71
High-temperature properties of	
brazed joints	120, 121
heat-resisting alloys (A)	42-48
stainless steels	36, 37
titanium alloys	86, 87
tool steels	26, 33
High-tin bronze, corrosion of	72
Hot extrusion, tool steels for	26, 27
Hot rolled steel	3
Hot shearing, tool steels for (T)	27, 28
Hot-top practice for killed steels	157
Hot trimming,	
tool steels for	26
Hot work tool steel,	
classification	21, 22
composition (T)	22
for coining dies	30
selection	25, 26, 32, 33
Hubbing molds, tool steels for	32, 33
Hydrocarbons, hazards	134
Hydroform type press for drawing titanium	81
Hydrogen,	
control of, in stainless steel	156
in steel making	155, 156
embrittlement in pickling steel	133
removal from steel melt	158

I

Impact extrusion of	
magnesium and its alloys	73, 74
Impact strength of brazed joints	120
Impregnation of powder metal parts	153
Inconel, See Heat-resisting alloys	43, 44, 47, 48
Induction brazing, tabulation (T)	122
Induction stirring in steel melting	155, 156
Infiltration of powder metal parts	153
Ingot molds for steel	155
Ingot practice in steel melting	157
Inhibited alloys	67
Inspection, nondestructive,	
selection of methods for (A)	159-163
Instrumentation in the Bessemer process	154
Internal-combustion engines, metal wear (A)	91-96
Iodide titanium	87, 88
Iron, recovery from slag	156
Iron-chromium alloys,	
grades for castings	47
production (F)	46
Iron-chromium-nickel alloys,	
compositions (T)	47
creep data for cast (T)	46
design of castings	46, 47
grades for castings	47
production (F)	46
rupture strength for cast (T)	46
stress-rupture properties (T)	48
Ironing of sheet steel	139

J

Jackman wedge roller (F)	108, 109
Jet tapper in steel melting	155
Jogging of	
stainless steel (10-8)	82
titanium and its alloys	82

Joining.	
See also <i>Welding and Brazing</i>	
aluminum and its alloys	56
copper and its alloys	66, 67, 71
magnesium	74
powder metal parts	153
stainless steel	41
titanium	85
Joints, bimetallic	76
Joints, brazed, See <i>Brazed joints</i>	115-122

K

K factor for nodular iron	51
Killed steel,	
hot-top practice	157
transition temperature range	2
Kohler illumination	164, 166
Kroll process for titanium	80

L

Ladle practice in steel melting	156, 157
Lake copper, composition (T)	85
Lap joints, See <i>Brazed joints</i>	
Larson-Miller method (stress-rupture)	43
Lathe tools, See <i>Machining</i>	
Leaded brass	64-71
Leaded bronze, composition (T)	65
Leaded commercial bronze, machinability (T)	67
Leaded copper	64, 67
Leaded copper alloys	64-71
Leaded high-strength yellow brass, cast (T_S)	69-71
Leaded naval brass, cast (T_S)	65, 67
Leaded nickel brass, cast (T_S)	69-71
Leaded nickel bronze, cast (T_S)	69-71
Leaded nickel silver, cast, composition (T)	65
Leaded red brass, cast	
composition, properties (T)	69-71
solidification temperature	71
strength vs section	71
Leaded semi-red brass, cast (T_S)	68-71
Leaded tin bronze, cast (T_S)	69-71
Leaded yellow brass, cast (T_S)	69-71
Leakage detection, methods for	161, 162
Liquid penetrant inspection	159
Low-alloy steel, See also Steel	
brazing	118-120
machining	146-148
selection (A)	1-20 ^F
weldability	4
Low brass	65
Low-carbon mold steels (T)	22
Low-carbon steel, See also Steel	
brazing	118-120
carbonitriding	125
cleaning	133
drawing	139
extrusion, cold	139, 140
machining	146, 148
selection	1-15
transition temperature range in impact-temperature tests	2
Low-leaded brass, machinability (T)	67
Low-leaded copper alloys, machining	66
Low-sulfur steel, production	155
Lubricant additives, effect on wear (P)	91
Lubricants for	
extruding steel	139
forming titanium	80-82

M

Machinability of	
cast iron	50, 145, 146, 148
copper alloys (T)	66, 67, 68, 70
corrosion resistant castings (T)	41
microstructure and	145
nodular iron	50, 146, 148
steel	146-148
titanium	82, 85
tool life and	145
tool steels (T)	24
Machining,	
chattering elimination	151
chipping failure	150
cost of production	148, 149
cutting fluid fundamentals	146, 147
cutting speed selection	149, 150
cutting tools	142, 144
economic depth of cut	150
economic feed	150
finish allowance, gray iron (T)	111
malleable iron	112
steel castings (T)	114
maximum production	149
milling cutter angles (T)	142
minimum cost	149
mode of tool failure	144
power requirements	144
process	141, 142
selection of speeds (T)	148, 149
tool geometry	141-144, 150, 151
tool life	144
tool life curves	146, 147
tool wear, progression of	144
turning speeds (T)	148
Machining of	
powder metal parts (A)	151, 152
steel and cast iron (A)	141-151

Magnesium and magnesium alloys (A)	... 73-77
adhesive bonding	74
anodizing (T)	74
applications	73, 75
ASTM designations for	73
brazing	116, 117, 122
casting	73
cathodic protection with	76, 77
cleaning and finishing	74, 75
coatings for	74
coding for (T)	74
creep properties (T)	76
design considerations	75, 76
designation system (T)	73
die casting molds, tool steels for	33
electromotive force series	76
electropolishing	74, 75
elevated temperature properties	75
fatigue properties (T)	75, 107
finished for	75-77
forging applications	73
galvanic corrosion	76, 77
grain refinement	73
HAE anodizing (T)	74
high temperature uses	75
hot extrusion, tool steels for	26
impact extrusion of	73, 74
index to alloys in 1948 Handbook	79
joining	76
machining	74
notch sensitivity	101
plastic coatings for	75
processing	73, 74
production data (T)	73
properties, data sheets	77, 79
riveting to dissimilar metal (P)	76
shot peening of	106
stress-rupture (P)	48
welding methods	74
zinc immersion coating (T)	74
Magnesium alloys, trade designations,	
See also <i>Magnesium and magnesium alloys</i>	

AZ31A,	
shot peening and fatigue (T)	106
strength/weight vs temperature (P)	86
EK 30 A, properties (T)	78
EK 30 A-T6,	
creep at elevated temperature (T)	76
properties at elevated temperature (T)	75, 76
EK 33 A, properties	78, 79
EK 41 A, properties (T)	78
EK 41 A-T5 and T6,	
creep at elevated temperature (T)	76
properties at elevated temperature (T)	75, 76
MIA,	
impact extrusion pressures (P)	74
ZK 51 A, properties	77-78
ZK 60 A, properties	77
Magnesium-aluminum-zinc-manganese,	
Mg - 8 Al - 0.7 Zn - 0.15 Mn,	
properties	78
Magnesium-rare earth-zinc-siliconium,	
Mg - 3.0 rare earth - 2.5 Zn - 0.6 Zr	
properties	78
Magnesium-rare earth-zirconium,	
Mg - 3.4 rare earth - 0.4 Zr, properties	
Mg - 4.0 rare earth - 0.7 Zr, properties	
Magnesium-zinc-siliconium,	
Mg - 4.5 Zn - 0.7 Zr, properties	
Magnetic particle inspection	160, 162
Magnetic properties testing	160, 163
Malleable iron,	
ASTM specifications	111
good design illustrated (P)	111-113
grade 32510	111
grade 35018	111
grade selection	111
machinability and microstructure	145
microstructure (P)	49
pearlitic	112
properties	111
section vs properties	111
Manganese brass	65, 67
Manganese bronze castings,	
applications	70-72
dezincification	72
fatigue limits	71
hot shortness	71
machinability	70
physical properties	72
shrinkage	70
strength vs section	71
Manganese wrought bronze,	
composition (T)	65
hot forming	65
tensile strength (T)	66
Manufacturers' standard gage for steel sheets	140
Mariempering, limitations	126
Martensite, definition	108
Martensitic stainless steels	10, 13
Mean stress, definition	108
Mechanical peening	105, 107-109
Medium-leaded brass, machinability (T)	66, 67
Medium-leaded copper alloys	66
Melting of steel (A)	154-158
Metal cutting	141, 142
article (A)	164-177
cathodic vacuum etching	169
color photomicrography, practice	167, 168
electrolytic polishing and etching	169-173
electron metallurgy	174-177
microscope	175
etching formulas (T)	172-173

Metallography (continued)	
extraction replica technique (P)	177
infra-red	167
metallurgical microscope	164, 165
phase contrast	165, 166
phase microscope	166
polishing formulas (T)	170-172
reagents (T)	170-173
precautions	169
ultraviolet	166, 167
Metal-to-metal wear (A)	91-96
Microscopes ,	
electron	175
metallurgical	164-165
optical, schematic (P)	174
Microscopy , See <i>Metallography</i>	
Microstructure of	
alpha brass (P)	167
cast iron, for wear resistance	92
chromium-nickel steel (P)	176
gray iron (P)	49, 145
gray iron for wear resistance (P)	92
heat resisting alloys	46
malleable iron (P)	49
molybdenum steel (P)	176
nickel, commercially pure (P)	167
nodular iron (P)	49, 50
titanium and alloys (P)	85
1081 carbon steel (P)	176
1087 carbon steel (P)	176
8640 steel, effect on tool life (P)	147
Mild steel , See <i>Steel</i>	
Milling ,	
cutter angles, carbides (T)	142
powder metal parts	152
titanium and alloys	82
tool materials for	23, 142
tooth geometry (P's)	143
Modulus , See under metal concerned	
Mold steels , tool steels for	22, 32, 33
Molds for steel ingots	155
Molybdenum in cast irons	52, 92
Molybdenum alloys , heat resisting	43, 48
Muntz metal (60 Cu - 40 Zn)	
composition (T)	65
dezincification of weld	67
fatigue limit, brazed joint in torsion (P)	119
hot forming after welding	67
N	
Naval brass	65-67
Navy G , modified	69
Ni-carbining (A)	124-126
Nickel ,	
braze joint strength vs temperature (P)	120
metallography	167, 171, 173, 176
nickel-base alloys (heat-resisting)	47-48
Nickel brass and bronze	72
Nickel-chromium brazing	121, 122
Nickel-chromium brazing filler metals	116, 117, 121
Nickel-chromium stainless steel	
See <i>Stainless steel</i>	
Nickel-copper alloys (T)	65
Nickel-copper-tellurium (T)	65
Nickel leaded bronze	69-71
Nickel-molybdenum steel, notch sensitivity (P)	101
Nickel silver,	
cast	68, 72
wrought, A and B (T)	64-67
Nickel-tellurium copper	66
Nimonic alloys, See <i>Heat-resistant alloys</i> , trade designations	
Nitralloy G, die applications	33
Nitriding of	
ferrous powder metal parts	153
steel for wear resistance	92, 93
Nitrocarburizing (A)	124-126
Nitrogen, removal from steel melt	158
in carbo-nitriding	124-126
Nitrogen atmospheres (T)	130B
Nitrogen control in Bessemer process	154
Nodular iron (A)	49-52
annealing	49
applications	52
austenitic, properties (T)	50
definition	49
ductility (T)	51
engineering properties	50-52
ferrite	50, 51
grades (T)	49
hardening, heat treatment	49, 50
heat treatment vs properties (P)	50
impact strength and toughness	51
K factor (P)	50
oxidation resistance	51
machinability (P's) (T)	50, 145, 146, 148
martensitic, properties (T)	50
microstructure (P)	49, 50
modulus of elasticity	51
notch sensitivity	51
pearlitic	49-51
physical properties (T)	52
processing	49, 50, 113
properties of various types (T)	50
rate of growth (P)	51
specifications (T)	49
strength at high temperatures (T)	51
strength to hardness ratio, K (P)	50
sulfur content	49
Nodular iron castings, See also <i>Nodular iron</i> , design of	112, 113
section thickness	112
tolerances	113

"Nondeforming" tool steels ,	
applications	23, 24
Nondestructive inspection ,	
aircraft turbine disks	162
chemical methods	161
detection of cold shuts in bushings	162
electrical methods	160
examples of	161, 163
factors in selection (T)	160
fluorescent penetrant inspection	159
heat-resisting metals	162
magnetic tests	160
methods and techniques (T)	161
optical methods	160
quality characteristics appraisable (T)	160
radiography	159
selection of methods for (A)	159-163
sonic and ultrasonic methods	159
sorting mixed lots of steel	163
thermal methods	160
weld soundness	161
Nonferrous alloys , See also metal concerned	
color photomicrography	167
effect of shot peening on fatigue strength (T)	107
Normalized steels , transition-temperature range	2
Notch sensitivity ,	
definition and terminology	101
fatigue strength and formula	3, 46
grain size and	101
radius of notch and stress concentration and	101, 102
stress-rupture tests	43
time of test	44
Notch sensitivity factor for aluminum alloys (P)	101, 102
gray iron	110
Haynes alloy 88 (P)	44
magnesium alloys	75, 101
nodular iron	51
steels (P's)	101, 102
titanium	81
Notched-bar impact tests	2
O	
Oil hardening tool steel	
applications	23, 24, 28
classification and composition (T)	22
high and medium alloy	26
low alloy	25
Oil quenching	126, 127
Open hearth steels , SAE-AISI tabulations	5
Ounce metal (85-5-5-5)	68
Oxygen-free copper	64-66
Oxygen in melting steel	155, 156, 158
P	
Pack carburizing	29, 130, 130A
Pack hardening of tools	26
Painting of	
aluminum assemblies (buses)	56
magnesium alloys and joints	75, 76
Pearlite ,	
in cast irons	49-51, 112
in machining	145-148
photomicrographs	145, 176
Pearlitic malleable iron castings	112
Peening ,	
See also <i>Shot peening</i>	
hand and mechanical	105, 107-109
Penetrants used in inspection	159
Perchloroethylene , hazards	134
Perchloric acid , hazards	169
Permanent mold castings	33, 55, 68
Phase contrast metallography	165-167
Phase microscope	165
Phosphor bronze , A-E, wrought,	
composition (T)	65
conductivity (T)	66
fatigue (T, footnote)	66
machinability	67
mechanical properties	64, 66
shot peened (T)	107
welding	67
Phosphor-deoxidized copper	64-67
Phosphorized copper	64-67
Photomicrography , See <i>Metallography</i> (A)	
Pickling of	
magnesium and its alloys	74
steel	132-134
tin and alloys	83
Piercing , dies for	28
sheet steel	136, 137
Piston pin bushings , automotive, (T)	96
Piston pins , automotive, design, materials, lubrication, finish and wear	95, 96
Piston rings , finished coatings, materials and wear factors	91, 93, 94
Piston rods , diesel engines	95, 96
Pistons , automotive, alloys for	55, 94
wear factors	91, 94
Plant standardization of steel	14, 15
Plaster casting	55, 68
Plastic coatings for magnesium	75
Plastic molds , tool steels for	32, 33
Plastic replica in metallography (P)	175, 176
Polishing and etching , electrolytic	169-173
Polishing compounds , removal of	132
Polishing titanium and its alloys	84, 153

Pouring practice in steel melting	155, 156, 157
Powder metal parts , (A)	151-153
ball-burnishing	152
coining	152, 153
finishing	153
heat treatment	153
impregnation and infiltration	153
joining	153
machining, speeds and feeds	152
tools for	152-153
sizing	153
Power factor control , automatic, in steel melting	155, 156
Press forming dies , tool steels for	29, 30
Press forming of sheet steel (A)	134-140
bending and forming	137
blanking	136
cold extrusion	139
costs vs method	135, 136
deep drawing	138
piercing	136
selection of method	135, 136
shaving	137
trimming	137
utilization of metal	140
Presses , types of metalworking	81, 82, 135
Pressure vessels , alloys for	42, 63-65, 67
Prestressing	105, 109
Production costs ,	
in forming steel	135, 136
in heat treating	128-130
in machining	148-150
Progressive dies	135
Projection welding , powder metal parts (P)	153
Pump shafts , automotive	96
Punches , tool steels for	26, 30
Q	
Quality control in shot peening	105
Quenching of	
carbonitrided carbon steels	126
constructional steels	6, 10, 15
Quenching mediums ,	
agitation (A)	126-127
comparison of water, oil and molten salt	126, 127
effect of agitation (P's)	126, 127
for tool steel (T)	24
R	
Radiographic gaging	159
Radiography ,	
of heat-resisting alloys	162
welded joints in steel	161
Radio-isotopes , availability of	159
Reagents for electrolytic etching , (T)	172, 173
precautions with	169
Reagents for electrolytic polishing , (T)	170-172
precautions with	169
Reamers , selection of tool steel for	23
Reaming of	
power metal parts	152
titanium and its alloys	82
Red brass	65, 66, 69
Refrigerant-resisting alloys	64
Replica techniques in microscopy	175-177
Resistance brazing (T)	122
Resistance welding of	
copper and its alloys	67
magnesium and its alloys	74
powder metal parts (P)	153
titanium and its alloys	82, 83
Riveted steel ,	
continuous casting	158
pouring practice	155
Rolling , for surface working	108
Rossi-Jungmans continuous casting machine	158
Rupture strength , definition	43
S	
Salt bath quenching	126, 127
Scale , removal methods	132, 133
Scarf joints , for brazing (P's)	115, 120
Scuffing wear in engines	91
Sealing compounds for joints	56, 76
Season cracking of copper alloys	67
Section thickness of castings	109, 110, 113, 114
Selection of	
alloy steels (A)	1-20F
aluminum alloys (A)	52-63
copper and copper alloys (A)	64-72
cutting speeds	149, 150
magnesium	75
metal cleaning methods (A)	131-134
nondestructive inspection methods (A)	159-163
stainless steel castings	40
tin and alloys	86, 87
tool steels (A)	21-23
Selenium copper	64, 65
Semi-killed steel , bottle-top molds for	157
transition temperature range (P)	2
SG iron , See <i>Nodular iron</i>	
Shafts , selection of steels for	10, 11
Shaving , sheet steel, allowances (T)	137
Shear blades , tool steels for	27, 28
Shell molding of aluminum alloys	55
Shock-resisting tool steels	21, 22, 26, 28

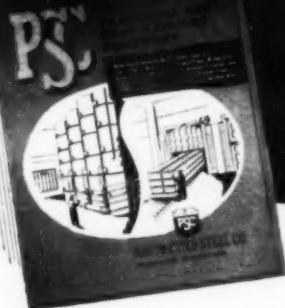
Shot peening (A)	104-108
Almen test strips for	106
applications	75, 103, 106, 107
definition	105
extent of improvement (F's)	105, 106
hand peening	105, 108, 109
process	104-106
to increase fatigue limit (F's)	103-106
to reduce stress concentration effects	103
Silicon-aluminum bronze	69-72
Silicon brass	68-72
Silicon bronze,	
cast	68, 69, 72
wrought	
fatigue limit (F)	119
selection factors	64, 67
Silicon-molybdenum steel (1.5 Si-0.5 Mo)	43
Silver-bearing coppers	65, 66
Silver brazing. See <i>Brazed joints (A)</i>	115-122
Single point tool, ABA nomenclature (P)	142
Sintered carbide. See <i>Cemented carbide</i>	
Sinterings, powder metal (A)	151-153
Sizing of	
powder metal parts	153
sheet steel	139
S-N diagram. See also <i>Fatigue limit</i>	108
Soil, removal from steel sheet	131
Solvent cleaning	131-133
hazards	134
Sonic testing	159
Sorting	160
combined with inspection of alloys	160, 162, 163
Spectroscopic testing	160
Spherical graphite iron. See <i>Nodular iron</i>	
Spot welding of	
copper and its alloys	67
magnesium and its alloys	74
powder metal parts	153
titanium (T)	83
Springs.	
automobile leaf	2, 6
carbon steels for	13
copper alloys for	64
treating of	64, 105, 107, 109
Stainless steel,	
article (A)	34-41
austenitic	34-39
braze joint strength (F's)	118, 120
cast	39-41
cleaning	132
composition limits (T)	34
ferritic	38, 39
HT, cast, stress-rupture (F)	48
heat treating	39
high-temperature behavior	42
joggling	82
martensitic	38
mechanical properties, annealed (T)	35
cold worked (T)	35
melting	156
physical properties, wrought (T)	36-37
production (F)	35
properties	35-38
shot peening for fatigue strength (T)	107
strength/weight ratio vs temperature (F)	86
welding	39
wrought	34-39
Stainless steel, trade designations	34-39
13-2, shot peening for fatigue strength (T)	106
18-8, shot peening for fatigue (T)	107
304 and 304L, stress-rupture (F)	48
316, stress-rupture (F)	48
347, properties vs temperature (F)	121
Stainless steel castings	39-41
Stainless steel sheet and strip,	
index to tolerances and limits (T)	140
Staking of powder metal parts	153
Standardization of steel grades	15
Steam turbines, service life	43
Steel,	
AISI products manuals, indexed (T)	140
AISI-SAE designations,	
See <i>Steel, SAE-AISI</i>	
availability from warehouse (T)	14
braze joints	118-120
brittle failures	2
carbonitriding (A)	124-126
carburizing	130, 130A
cold drawing vs strength (F)	4
comparison with titanium	86
continuous casting	157, 158
damping capacity	110
extrusion, process	139-140
tool steels for	27, 30
fatigue	1, 100-108
data (F)	101, 102, 107
failures in (F)	97-100
terms, definition	108
vs size, formula (footnote)	103
forming of sheet (A)	134-140
hardenability	4, 6, 10, 11, 16-20E
hardening, depth of	6, 7
hardness vs properties (F's)	12
heat treating, costs (A)	128-130A
procedures	6, 10, 124-127
machinability	146-148
machining costs	148-150
machining of (A)	141-151
mechanical properties	5, 12, 13
melting	154-158
notch sensitivity, toughness (F)	3, 101, 102
plant standardization problem	14
properties, correlation of (F's)	12
Steel (continued)	
purchasing by mill heat	14, 140
selection by hardenability	14
cost (T)	11
depth of hardening (T)	11, 16-20E
engineering considerations	1
selection, for cold extrusion	139
for constructional use (A)	1-15
shot peening (A)	104-108
sorting of mixed lots	163
standardization of grades	15
Steel, SAE-AISI. See also <i>Steel</i>	
composition limits, C steels (T)	3
H-steels (T)	7, 16-20E
standard alloy steels	20F
hardenability bands, H-steels	16-20E
machinability (F's) (T)	146-148
properties (T)	5
selection by hardenability (T)	11, 14, 16-20E
warehouse stock (T)	14
Steel castings,	
ASTM specifications	114
design	113-114
dimensional tolerances (T)	114
machine finish allowances (T)	114
Steel forgings, cleaning	132, 133
Steel melting (A)	154-158
basic electric furnace melting	155
basic open hearth process	154
Bessemer process	154
continuous casting of steel	157
ingot and pouring practice	156
vacuum and atmosphere melting	158
Steel melting furnaces,	
basic electric	155, 156
basic open hearth	154
induction	158
vacuum	158
Steel sheet,	
bending and forming	137, 138
blanking	136
cleaning	131
cutting clearances in blanking	136
deep drawing	138, 139
forming (A)	134-140
ironing	139
picking	133
piercing	136, 137
purchasing	14, 140
removal of drawing compounds	131
shaving	137
sizing or striking	139
thickness ordering ranges	140
trimming	137
utilization	140
Steel sheet and strip, tolerances and limits	
index (T)	140
Steel tubing, magnetic testing for surface defects	163
Steels, SAE-AISI, trade designations,	
C1006 to C1151,	
applications	4-15, 92-96
composition limits (T)	3
fatigue data (F's)	101, 102
machinability data (F's) (T)	146-148
properties of cold drawn bars (T)	5
hot rolled bars (T)	5
selection	10-15
by hardenability (T)	11
shot peened for fatigue (T)	105, 107
size variations (T)	4
warehouse availability (T)	14
1020,	
braze joint shear strength (F)	118
butt joint, strength (F)	118
compared with 1018	15
fracture, ductile to brittle (F)	2
influence of cutting fluids on (T)	148
scarf joint strength vs temperature (F)	120
1020, carbonitrided,	
carbon and nitrogen gradients (F)	124
end-quench hardenability (F)	125
hardness gradient (F)	124
microstructure (F)	124
1020, normalized, notch sensitivity (F)	101
1025, fracture, ductile to brittle (F)	2
1042, hardenability test values (T)	6
1112, milling, use of charts on angles (F)	143
1330 to 9850 and 86B45-H,	
applications	4-15, 92-96
composition limits	20F
fatigue data (F's)	101, 102
machinability data (F's) (T)	146-148
selection	10-15
selection by hardenability (T)	11
shot peened for fatigue (T)	105, 107
warehouse availability (T)	14
1020,	
braze joint shear strength (F)	118
butt joint, strength (F)	118
compared with 1018	15
fracture, ductile to brittle (F)	2
influence of cutting fluids on (T)	148
scarf joint strength vs temperature (F)	120
1020, carbonitrided,	
carbon and nitrogen gradients (F)	124
end-quench hardenability (F)	125
hardness gradient (F)	124
microstructure (F)	124
1020, normalized, notch sensitivity (F)	101
1025, fracture, ductile to brittle (F)	2
1042, hardenability test values (T)	6
1112, milling, use of charts on angles (F)	143
1330 to 9850 and 86B45-H,	
applications	4-15, 92-96
composition limits	20F
fatigue data (F's)	101, 102
machinability data (F's) (T)	146-148
selection	10-15
selection by hardenability (T)	11
shot peened for fatigue (T)	105, 107
warehouse availability (T)	14
1340, fatigue tests on steering knuckle (T)	105
4000 series, engine tappets	94
4130, stress-deformation tests (F)	44
4140, braze joint, shear strength (F)	118
butt joint, strength (F)	118
carbonitrided, heavy-duty gears	126
engine cylinders	92
4340, carbonitrided, heavy-duty gears	126
fatigue data	105
5115, piston pins	95
5120, engine tappets	94
5140, carbonitrided, heavy-duty gears	126
8640, carbonitrided, heavy-duty gears of	126
effect of heat treatment and micro-structure on tool life (F)	147
machinability (T)	148
selection of cutting speed	150
tool life curves (F)	146, 147
9400, quenching-cooling rates (F)	126
Steels, SAE-AISI, H-steels,	
1330-H to 9850-H,	
applications	4-15, 92-96
compositions (T's)	16-20E
hardenability bands (F's)	16-20E
hardness limits specification (T)	8-9
selection by hardenability (T)	11
3310-H, range of core hardness	14
4140-H, fracture, ductile to brittle (F)	2
4817-H, machinability (T)	148
8635-H, minimum hardenability (F)	10
8650-H, minimum hardenability (F)	10
8720-H, carburizing cost problem	128
9262-H, machinability (T)	148
Stockroom standardization of steel grades	15
Strain gage analysis of castings	110
Stress analysis	1, 110
Stress formulas	97
Stress concentration,	
application to brittle and ductile metals	100
article (A)	97-103
definitions	97, 100
design improvements	100-103
fatigue failures resulting from (F's)	97, 100
in brazed joints	117
notch sensitivity and	101, 102
surface improvement	2, 103, 104-108
Stress concentration factor,	
definition and formula	97, 108
values for several configurations (F's)	98-100
Stress concentration factors,	
combined factor, definition	100
for several configurations (F's)	98, 99
Stress corrosion cracking, copper alloys	64, 67
Stress distribution,	
improvements in	103
in brazed joints	119
Stress ratio, definition	108
Stress relieving of	
copper alloys	67
deep drawn steel	139
nodular iron	49, 112
titanium alloy parts	81, 83
Stress-rupture of	
aluminum alloys (F)	53
Haynes alloy 88 (F)	44
N-155 alloy (F)	45
nodular iron (F)	51
S-590 alloy (F)	43
V-36 alloy (F)	45
Stress-rupture tests	42-44
Stress vs creep rate,	44
design curves for	45
Stress vs deformation,	44, 45
design curves for	45
Stresses, residual surface,	
effect on fatigue strength	105
Stretch forming of titanium	81
Striking of sheet steel	139
Submerged-arc welding of copper alloys	67
Surface finish, See Surface roughness value	
Surface hardening of	
ferrous powder metal parts	153
titanium and its alloys	83
Surface rolling,	
advantages and disadvantages	105
crankshaft fillet (F)	104
extent of improvement of strength	104
magnesium alloys	75
process and tooling	108, 109
Surface roughness value,	
braze, joint preparation	122
engine parts	92-96
machining, design of tool	151
Surface working, See Shot peening, Surface rolling, and Prestressing	
T	
Tantalum carbide in cutting tools	142
Tappets, engine,	
alloys for	94
design of and design data	94, 95
finishes for	94
types (F)	94
Tapping of	
powder metal parts	152
titanium and its alloys	82
Taps, selection of tool steel	23
Tellurium copper	64, 65
Tellurium-nickel-copper	65, 66
Tempering of	
case in carbonitriding	125
nodular iron	49
steel	12
tools	26
Tempers,	
designations for aluminum (T)	73
designations for magnesium (T)	73
Tensile strength/density ratio vs temperature	86
for eight alloys (F)	63
Ternalloy 5 and 7	63
Testing, nondestructive (A)	159-163
Testing equipment for	
nondestructive inspection	159-163
Testing for soundness	159-163
Testing for thickness	159
Testing of heat-resisting alloys,	
creep tests	44
nondestructive	162
short-time tension tests	42
stress-rupture tests	42-44
Tetrachloroethylene, hazards with	134
Tetraethyl lead, effect on valve seats	95
Thermal conductivity of	
copper alloy castings	72
copper and its alloys (T)	64, 66

Thermal inspection methods	166
Thread-cutting dies, tool steels for	23
Thread gages, tool steels for	32
Thread rolling dies, tool steels for	31
"Through hardening" steels, selection by cost (T)	11
Tin bronze, castings	68-71
Tin in copper alloys, embrittlement	69
Tin mill products,	
cleaning	133
index to tolerances and limits (T)	149
Titanium and Titanium alloys (A)	80-89
annealing	80, 83
anodizing	83, 84
applications	85, 87, 88
available forms	85
bending radii for sheet (T)	81
cleaning and finishing	83
corrosion resistance of	83
creep properties (F)	86-89
design	85, 86
elevated-temperature properties	86, 87
fatigue limit and fatigue ratio	86
forging of	80, 81
forgings, bars and rods, properties (T)	87
forming of sheet	81
heat treatment of	83
Kroll process	89
machining and grinding	82
metallurgy of	84, 171, 172
mill forms, production of	89
notch sensitivity of	81
oxidation of	80
production 1948-1953	80
production of ingots	80
properties, all temperatures	86-89
seam and spot welding of (T)	83
selection of	86, 87
sheet, strip and plate properties (T)	87
strength/weight ratio at 300-700 F	89
stress-rupture	88-89
stretch forming of	81
welding of	82, 83
Titanium (99.0 Ti), data sheet	88
Titanium (99.2 Ti), data sheet	88
Titanium (99.9 Ti), data sheet	87
Titanium-aluminum-chromium.	
Ti-3 Al-5 Cr, properties (T's)	87, 89
Titanium-aluminum-chromium-iron-molybdenum.	
Ti-5 Al-14 Cr-1.3 Fe-1.3 Mo, properties (T's)	89
Titanium-aluminum-manganese.	
Ti-4 Al-4 Mn, properties (F) (T's)	86, 87, 89
Titanium-aluminum-tin.	
Ti-5 Al-2.8 Sn, properties (T's)	87, 89
welding	82
Titanium carbide in cutting tools	142
Titanium-chromium-iron-oxygen.	
Ti-2.7 Cr-1.3 Fe-O, properties (T)	87
Titanium-iron-chromium-molybdenum.	
Ti-2 Fe-2 Cr-2 Mo, properties (T's)	87, 89
Titanium-manganese, Ti-8 Mn, properties (F) (T's)	86, 87, 89
Tolerances, dimensional, for corrosion-resistant castings	40
ferrous castings	111-114
sheet metal parts	135
Tool life for	
maximum production	149, 150
minimum cost	149, 150
Tool life of cutting tools	142, 144-146
Tool life curves (F's)	50, 146, 147
Tool steel, See also Tool steel selection for	
air-hardening	
composition and classification (T)	22
for blanking	28
for die blocks and die inserts	26
for extrusion dies	26, 30
for forging machines	26
for thread rolling dies	31
for trimming dies	26
medium-alloy cold work	22
carbon-tungsten	22
characteristics of groups compared (T)	24
chromium hot work	22
classification (T)	22
classification cross-index (T)	21
comparison of attributes (T)	24
compositions (T)	22
cost, relative (T)	24
decarburization tendency (T)	24
designation cross-index (T)	21
distortion in hardening (T)	24
grades	22
hardenability, depth of (T)	24
hardening temperature range (T)	24
hardness, recommended (T)	24
heat resistance (T)	24
high-carbon high-chromium cold work	22
high-cobalt cutting tools	25
high speed,	
choice of grade	24, 25
composition and classification (T)	22
for blanking	29
for cold extrusion dies	30
for cutting tools	24
for thread rolling dies	31
for trimming dies	26
molybdenum compared with tungsten	25
selection	25, 26
identification cross-index (T)	21
low-alloy special-purpose, type L	22, 24
low-carbon mold	22
machinability (T)	24
molybdenum high speed	22

Tool steel (continued)	
molybdenum hot work	22
"non-deforming" characteristics (T)	24
oil-hardening	
cold work	22
composition and classification (T)	22
for blanking	28
for cutting tools	23
for die blocks and die inserts	25-26
for die casting dies	33
pretreated	25
applications (T)	25
hardness ranges of (T)	25
quenchants recommendations (T)	24
required characteristics vs use (T)	23
safety in hardening (T)	24
selection, See Tool steel selection for shock-resisting (T)	22
toughness (T)	24
tungsten high speed	22
tungsten hot work	22
types (T)	21, 22
water-hardening (T)	
composition and classification (T)	22
for blanking	28
for cold heading	30
for cutting tools	23
for die blocks and die inserts	25
for die casting dies	33
for drawing and forming	29
for gages	31
for plastic molds	32
wear resistance (T)	24
Tool steel, AISI-SAE,	
available types (T's)	21, 22
classification (T)	22
compositions (T)	22
Tool steel, AISI-SAE to ASM cross index	21
Tool steel selection for	
blanking and piercing dies	28, 29
coining dies	30
cold extrusion dies	39
cold heading dies	30, 31
cold work operations (T)	22
crowners	26
cutoff tools	26
cutting tools	23
die blocks and die inserts, cold heading	25, 26, 30, 31
die-casting dies	33
die inserts	30
dies and punches	29
drawing cups	29, 30
drawing titanium	61
drawing wire, bar, and tubes	27
drills	23
extrusion dies	26, 27
forging machines	26
forming	29
gages	31, 32
gripper and header dies	26
hot extrusion	27
molds, copper castings	33
nut dies	36
permanent molds	33
piercers and punches	26
piercing dies	28, 29
plastic molds	32, 33
punching thin materials	29
rollers, surface working	108
severe service dies	39
shearing	27, 28
solid shear blades	27, 28
thread gages	32
thread rolling dies	31
trimming dies and trimming tools	26
wire drawing	27
Tooling,	
machining, production cost	148, 150
press-forming, cost vs choice	135, 136
production, press forming	
comparative costs vs methods (F)	135, 136
multiple-operation	135
short-run	134
single-operation	135
Tools,	
broaching, for powder metal parts (P)	152
burnishing,	
for powder metal parts (P)	152, 153
machining, for powder metal parts (P)	152
stress concentration failures (F)	97, 100
surface condition	26
Toughness in tool steel (T)	24
Toxicity of industrial solvents	134
Transfer presses	135
Transmission line, aluminum	57
Tribo-electric effect	160, 163
Trichloroethylene, hazards with	134
Trimming of sheet steel	26, 137
Trucks,	
aluminum usage in	55
life testing	2
Tubing, thin-wall	
current manufacturing process	59
Tumbling of parts, cleaning methods	132, 133
Tungsten carbide dies	27
Tungsten finishing steel,	
See Toolsteel, water-hardening	
Tungsten high speed tool steel	22-26, 28-31
Turbo-jet engines	43, 85, 162
Turning of	
powder metal parts	152
steel,	
cutting speeds (F) (T)	146-148
tool geometry	141-144, 150, 152
titanium and alloys (T)	82
U	
Ultrasonic cleaning	132
immersed	162
Ultraviolet metallography	166-167
Unfired pressure vessel code of ASME,	
for design strength values	64
Upsetting of screws, rivets and bolts	65
V	
V_{sh}, cutting speeds for steels and cast irons (T)	146, 148
Vacuum and atmosphere melting of steel	158
Vacuum melting furnaces for steel (P)	158
Vacuum metallizing in microscopy	176
Valve bronze, See Lead-tin bronze	
Valve guides, materials used	95
Valve seats, effect of fuels on inserts, metals used	95
Valves,	
alloys and treatment for finishes and coatings	95
Vanadium tool steel	25
Vapor degreasing	131, 132
Vibration in designing with titanium	85, 86
Von Bolton arc melting of titanium	80
W	
Water-hardening, low-alloy die steels	25
Water-hardening tool steel, See Tool steel, water-hardening	
Water quenching	126, 127
Wear land on a cutting tool	146, 147
Wear of engine parts,	
bearings	96
camshafts and tappets	94, 95
crankshafts	96
cylinders and liners	91, 93
pistons and rings	93, 94
piston pins and bushings	95, 96
service conditions	91
valves, seats, guides	95
water pump shafts	96
Wear of metals in engines (A)	91-96
engineering design	94-96
plated finishes	92-96
selection of metals	92-96
Wear resistance of	
chromium-plated engine cylinders	92, 93
chromium-plated piston rings	93, 94
copper alloy castings	71
engine valve guides	95
engine valve seats	95
gray iron	93
nodular iron castings	113
piston rings	93, 94, 95
tool steels (T)	23, 24
white iron castings	111
Weided joints, nondestructive inspection	161
Welding of	
aluminum	56, 57
copper alloy castings (T)	71
copper and alloys	67
magnesium and alloys	74
powder metal parts	153
stainless steel castings (T)	41
stainless steel wrought alloys (T)	39
steel, inspection of	161, 162
titanium and its alloys (T)	82, 83
Welding, braze-, definition	115
Welding rods,	
ASTM specification (T, footnote)	116
for copper and its alloys	66, 67
Welding vs riveting, comparative costs on aluminum	57
White iron castings,	
ASTM specification	111
compressive strength	111
design and applications	111
wear resistance	111
"White" steel sheet, definition	133
Wire,	
current carrying capacities	57
music, shot peened for fatigue (T)	106
spring (0.85% C), shot peened (T)	106
Wood-magnesium joints	76
Work hardening in deep drawing of steel	139
Y	
Yellow brass, cast	68, 69
Yield strength, definition of,	
for copper and copper alloys	64
for heat-resisting alloys	42
Yield strength vs tensile strength for cold drawn and hot rolled steel	4
nodular iron	51
Z	
Zinc in	
bronze bushings	96
tin bronzes	71
Zinc chromate primer for	
aluminum and its alloys	56, 57
magnesium-dissimilar metals	76
Zinc immersion treatment for	
magnesium and its alloys (T)	74, 75

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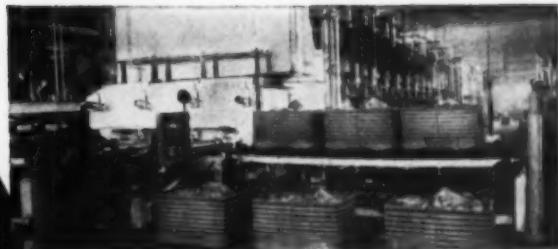


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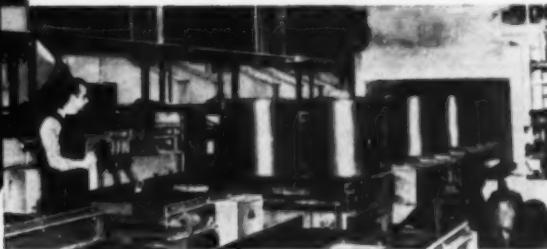
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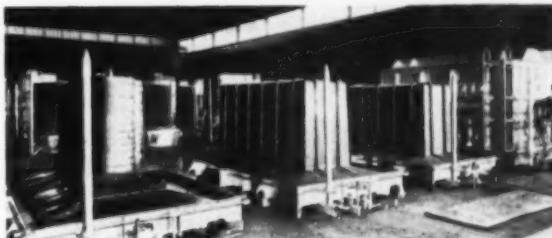
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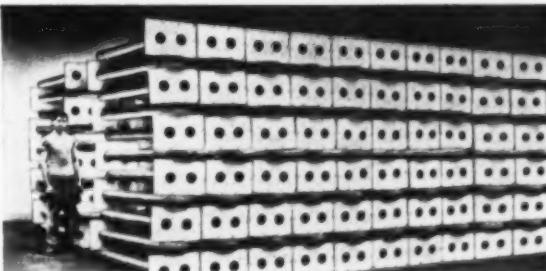
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PRODUCT*	NOMINAL COMPOSITION	USES
BORON ALLOYS		
Ferroboron Min. 10.0%	Aluminum max. 0.50%	Increases hardenability of steel; also, for additions to malleable iron and aluminum alloys.
Boron Grade Min. 17.50%	Carbon max. 1.50%	
Boron Grade	Aluminum max. 0.50%	
Manganese-Boron	Carbon max. 0.50%	
Boron min. 17.50%		Used to cleanse and deoxidize non-ferrous alloys.
Manganese approx. 7.5%		
Carbon max. 3%		
Iron max. 5%		

CALCIUM ALLOYS		
Calcium-Silicon	Calcium 30 to 33%	Deoxidizer for quality ingot steel. Also used in high-tensile gray irons.
	Silicon 60 to 65%	
	Iron 1.50 to 3%	
Calcium-Manganese-Silicon	Calcium 16 to 20%	A complex deoxidizer used widely in production of steel castings.
	Manganese 14 to 18%	
	Silicon 53 to 59%	
Calcium Metal Regular Grade	Calcium 98%	Reducing agent in metallurgical applications, deoxidizer and degasser for non-ferrous metals.
	Balance largely Calcium Chloride	
Distilled Grade	Calcium approx. 99.50%	For special applications requiring calcium of very high purity.
	Balance largely Magnesium	

CHROMIUM ALLOYS		
"Simplex" Low-Carbon Ferrochrome	Chromium 63 to 66%	
	Silicon 5 to 7%	
	Carbon max. 0.010% or 0.025%	
2% Nitrogen-Bearing Grade	Chromium 62 to 65%	For producing stainless steel, particularly the low-carbon grades. The silicon in the alloy reduces metal oxides from the slag back into the bath. Rapid solubility of the alloy saves furnace time.
	Silicon 5 to 7%	
	Nitrogen 2 to 2.5%	
	Carbon max. 0.025%	
5% Nitrogen-Bearing Grade	Chromium 60 to 63%	
	Silicon 5 to 7%	
	Nitrogen 5 to 6%	
	Carbon max. 0.025%	
Low-Carbon Ferrochrome (Other Grades)	Chromium 67 to 71%	Production of stainless steels and high-temperature alloys requiring low carbon content.
	Silicon 0.30 to 1.00%	
	Carbon (10 Grades) max. 0.02 to max. 2.00%	

High-Carbon Ferrochrome Max. 4.50, 5.00, or 6.00% Carbon Grade	Chromium 67 to 70%	
	Silicon 1 to 2%	
Max. 7.00% Carbon Grade	Chromium 66 to 69%	For production of engineering alloy steels and other alloy steels of moderate chromium content.
	Silicon 1 to 3%	
Min. 7.00% Carbon Grade	Chromium 65 to 68%	
	Silicon 1 to 3%	
5% to 62% Chromium Grade	Carbon max. 5 or 6%	
	Silicon max. 3.5 or 4%	
Nitrogen-Bearing Low-Carbon Ferrochrome	Chromium 65 to 70%	For additions of nitrogen to improve properties of high-chromium steels.
	Silicon 0.30 to 1.00%	
	Carbon max. 0.10%	
	Nitrogen 0.75 to 2.00%	

"SM" Ferrochrome	Chromium 60 to 65%	
	Silicon 4 to 6%	
	Carbon 4 to 6%	
	Manganese 4 to 6%	
Exothermic Ferrochrome	Chromium approx. 60%	These improved exothermic ladle alloys have high solubility, low carbon pickup, and high ignition temperature.
	Carbon max. 4.5%	
Exothermic Silicon-Chrome	Chromium approx. 46%	
	Silicon approx. 23%	
	Carbon max. 1.00%	
Foundry Ferrochrome High-Carbon Grade	Chromium 62 to 66%	Developed especially for high-solubility ladle additions of chromium to improve composition and properties of cast iron.
	Silicon 7 to 10%	
	Carbon 5 to 7%	
	Chromium 50 to 54%	
	Silicon 28 to 32%	
	Carbon max. 1.25%	

PRODUCT*	NOMINAL COMPOSITION	USES
CHROMIUM ALLOYS cont.		

Chromium Metal Low-Carbon Grade	Chromium min. 97%	
	Carbon max. 0.10%	
	Iron max. 1%	
Nitrogen-Bearing Grade	Above grade with Nitrogen approx. 0.75% or higher.	Production of wide variety of non-ferrous chromium-bearing alloys, including electrical resistance alloys and high-temperature alloys.
High-Carbon Grade	Chromium 87 to 90%	
	Carbon 9 to 11%	
	Iron max. 1.25%	
Electrolytic Chromium Laboratory Grade	Chromium min. 99.20%	
	Iron max. 0.03%	
Commercial Grade	Chromium min. 99.00%	
	Iron max. 0.30%	
"EM" Ferrochrome-Silicon	Chromium 39 to 41%	Used in production of stainless steel to reduce metal oxides from the slag back into the bath.
	Silicon 42 to 46%	
	Carbon max. 0.05%	
"EM" Ferrosilicon-Chrome	Chromium 50 to 54%	For adding chromium and silicon to steels containing up to 1 or 2 per cent chromium.
	Silicon 28 to 32%	
	Carbon max. 1.25%	
"EM" Chromium Briquets (Hexagonal Shape)	Chromium 2 lb. Total Weight 3% lb.	For adding chromium to cast iron in the cupola.

COLUMBIUM ALLOYS		
Ferrocolumbium	Columbium 50 to 60%	Stabilizer in austenitic chromium-nickel stainless steels. Also constituent of high-temperature alloys.
	Silicon max. 8%	
	Carbon max. 0.40%	
Ferrotantalum-Columbium	Columbium approx. 40%	Used to supplement ferrocolumbium in chromium-nickel stainless steels and high-temperature alloys.
	Tantalum approx. 20%	
	Cb + Ta min. 60%	
	Silicon 5 to 7%	
	Carbon max. 0.30%	

MANGANESE ALLOYS		
Standard Ferromanganese Regular Grade	Manganese 74 to 76%	Most common means of adding manganese to steel for both alloying and deoxidizing purposes. Also for counteracting sulphur in steel and cast iron.
	Carbon approx. 7%	
	Silicon max. 1%	
Low-Phosphorus Grade	Manganese 78 to 80%	
	Carbon max. 7%	
	Silicon max. 2%	
	Phosphorus max. 0.10%	
Low-Carbon Ferromanganese Low-Phosphorus Grade Regular Grades	Manganese min. 90%	Additions of manganese to steels of low-carbon specification, particularly stainless steels of 18 per cent chromium, 8 per cent nickel type.
	Carbon max. 0.07%	
	Phosphorus max. 0.06%	
	Manganese 85 to 90%	
	Carbon max. 0.07, 0.10, 0.15, 0.30 or 0.50%	
Regular Grade (High-Silicon)	Manganese 80 to 85%	
	Silicon max. 0.75%	
	Silicon 5 to 7%	
"Mansiley" Alloy	Manganese 60 to 63%	Used in production of stainless steels to reduce metal oxides from the slag back into the bath.
	Silicon 28 to 31%	
	Carbon max. 0.07%	
	Phosphorus max. 0.05%	

Silicomanganese Max. 1.50% Carbon Grade	Manganese 65 to 68%	A versatile alloy useful as furnace block, deoxidizer, and also for making manganese additions to steel in the ladle or in the furnace.
	Silicon 18 to 20%	
Max. 2.00% Carbon Grade	Manganese 65 to 68%	
	Silicon 15 to 17.50%	
Max. 3.00% Carbon Grade	Manganese 65 to 68%	
	Silicon 12 to 14.50%	
Medium-Carbon Ferromanganese	Manganese 80 to 85%	For making low- and medium-carbon manganese steel and Hadfield steel.
	Carbon 1.25 to 1.50%	
	Silicon max. 1.00 to 1.50%	

*All of the alloys and metals listed are produced in the usual lump, crushed, or ground sizes, except where other special forms are indicated.

PRODUCT*	NOMINAL COMPOSITION	USES	PRODUCT*	NOMINAL COMPOSITION	USES
MANGANESE ALLOYS cont.					
Low-Iron Ferromanganese	Manganese 85 to 90% Carbon approx. 7.00% Silicon max. 3% Iron max. 2%	For high manganese additions to certain non-ferrous alloys, particularly aluminum.	Magnesium-Ferrosilicon	Silicon 43 to 47% Magnesium 7.5 to 9.5% Cerium approx. 0.50%	For addition to cast iron and steel to obtain special properties.
Manganese Metal	Manganese min. 95.50% Carbon max. 0.20% Silicon max. 1.00% Iron max. 2.50%	Used both as deoxidizer and alloy in production of numerous non-ferrous metals and alloys.	Cerium-Bearing Grade		
"EM" Silico-manganese Briquets (Square Shape)	Manganese 2 lb. Silicon ½ lb. Total Weight 3½ lb.	For adding manganese (with silicon) to cast iron in the cupola.	TITANIUM ALLOYS		
"EM" Ferro-manganese Briquets (Oblong Shape)	Manganese 2 lb. Total Weight 3 lb.	For adding manganese (without silicon) to cast iron in the cupola.	Ferrotitanium	Titanium 27 to 32% Carbon max. 0.10%	For stabilized stainless steels and high-temperature metals.
SILICON ALLOYS					
50% Ferrosilicon	Silicon 47 to 51%		Silicon-Titanium	Titanium 40 to 50% Silicon 45 to 50% Iron max. 3%	For additions of titanium to steels or non-ferrous alloys.
Regular Grade	Silicon 47 to 51%		Manganese-Nickel-Titanium	Titanium 43 to 48% Nickel approx. 25% Manganese max. 8%	Deoxidization of nickel alloys.
Blocking Grade	Silicon 47 to 51%				
Boron-Bearing Grade	Silicon 47 to 51% Boron 0.035 to 0.045%	Deoxidizer for most grades of killed or semi-killed steel. Blocking grade specially sized for maximum efficiency.			
Low-Aluminum Grade	Silicon 47 to 51% Aluminum max. 0.40% or 0.10%				
65% Ferrosilicon	Silicon 65 to 70%	For furnace or ladle addition to steels.	TUNGSTEN ALLOYS		
Regular Grade	Silicon 61.50 to 66.50% Aluminum max. 0.50% Total Impurities max. 1.00%	Mainly for production of electrical sheet steel.	Ferrotungsten	Conforming to A.S.T.M. Spec. A 144-50	Production of tool and die steels; also high-temperature alloys.
Low-Impurity Grade					
75% Ferrosilicon	Silicon 73 to 78%	Deoxidizer and alloy for production of high-silicon spring and electrical sheet steel. Graphitizing inoculant for cast iron.	Tungsten Metal Powder		
Regular Grade	Silicon 73 to 78%		Melting Grade	Tungsten min. 98.80% Total Carbon max. 0.25%	Production of tungsten steel and cast tungsten carbide.
Low-Aluminum Grade	Aluminum max. 0.50%				
85% Ferrosilicon	Silicon 83 to 88%		Calcium Tungstate	Tungstic Oxide 68 to 72%	For making tungsten chemicals and other tungsten products.
Regular Grade	Silicon 83 to 88%		Calcium Tungstate Nuggets	Tungstic Oxide 68 to 72%	Making tool steels and high-temperature alloys.
Calcium-Bearing Grade	Calcium min. 0.50%				
Low-Aluminum Grade	Silicon 83 to 88% Aluminum max. 0.50%	Enables melter to add higher percentages of silicon without chilling metal in ladle. Graphitizing inoculant for cast iron.	Ammonium Paratungstate	Tungstic Oxide min. 88.7%	Intermediate for tungsten products.
90% Ferrosilicon	Silicon 92 to 95%				
Regular Grade	Silicon 92 to 95%	Permits large additions of silicon without harmful chilling effect.	VANADIUM ALLOYS		
Low-Aluminum Grade	Aluminum max. 0.50%		Ferrovanadium	Vanadium 50 to 55% or 70 to 75% Carbon max. 0.20, 0.50, or 3.00% Silicon max. 1.50, 2.00, or 8%; and approx. 10%	Production of tool and engineering steels, high-strength structural steels, non-aging rimming steels, and wear-resistant irons.
Silicon Metal	Silicon min. 97 or 96% Iron max. 1 or 2%	Additions of silicon to non-ferrous metals, particularly aluminum and copper.	Vanadium Oxide Fused	Vanadium 86 to 89% Na ₂ O approx. 10% CaO approx. 2%	For addition of vanadium to steel and for manufacturing catalysts.
Regular Grade			Sodium Polyvanadate (Red Coke)	Vanadium approx. 85% Na ₂ O approx. 9%	For manufacture of vanadium compounds, including vanadium catalysts.
Purified Grade	Silicon 99.70 to 99.90% Iron 0.05 to 0.015%	For applications in non-ferrous industry requiring silicon of high purity.	High-Purity Ammonium Metavanadate	Vanadium approx. 99.50% NH ₄ VO ₃ min. 99%	
Low-Calcium Grade	Silicon min. 97% Iron max. 1% Calcium max. 0.10%	For high-silicon aluminum alloys where calcium is detrimental.			
Low-Aluminum Grade	Silicon min. 98% Iron max. 1% Aluminum max. 0.10%	For the production of silicon-copper alloys where aluminum is detrimental.	ZIRCONIUM ALLOYS		
"SMZ" Alloy	Silicon 60 to 65% Manganese 5 to 7% Zirconium 5 to 7%	Particularly strong graphitizing inoculant used in cast iron.	12 to 15% Zirconium Alloy	Zirconium 12 to 15% Silicon 39 to 43% Carbon max. 0.20%	A powerful deoxidizer. Also increases depth of hardening.
"EM" Silicon Briquets	Silicon 2 lb. Total Weight 5 lb.	For adding silicon to cast iron in the cupola.	35 to 40% Zirconium Alloy	Zirconium 35 to 40% Silicon 47 to 52% Carbon max. 0.50%	Deoxidizer for fine grades of alloy steels.
Large Size (Cylindrical or Brick-Shape)			"EM" Zirconium Briquets (Cylindrical Shape, Reddish Color)	Zirconium 0.55 lb. Silicon 1.90 lb. Total Weight 5 lb.	For adding zirconium and silicon to cast iron in the cupola.
Small Size (Cylindrical Shape)	Silicon 1 lb. Total Weight 2½ lb.				

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PERSONAL MENTION

Brief biographies of the members of the ASM Metals Handbook Committee and chairmen of the technical committees whose reports appear in this issue



Edgar O. Dixon

Edgar O. Dixon

Chairman

ASM Metals Handbook Committee

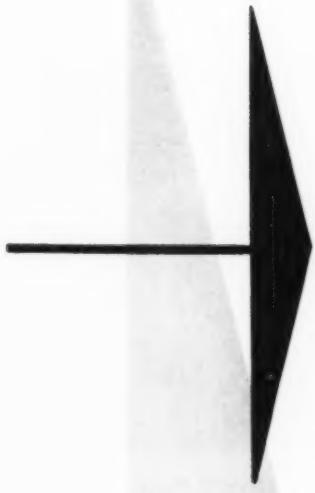
ED DIXON is an engineer, metallurgist, research executive and chairman of the ASM Metals Handbook Committee. As vice president in charge of research and metallurgy for Ladish Co., his responsibilities cover a wide range of problems associated with the production of forgings. Following these products

through to their many applications takes him into most parts of the metalworking industry, as well as many other metal-using industries. His breadth of experience and his great interest in the orderly presentation of engineering information combine to give Dixon an exceptionally well balanced view and to make him a truly effective leader of the ASM's Handbook activities.

After completing his formal technical education at the University of

Illinois, he went with International Harvester Co., in 1919. He was chief metallurgist of that company's roller bearing and magneto plant for five years before joining Ladish in 1928. Since then he has covered the entire gamut of open and closed die forgings, from steel pipe line fittings to titanium gas turbine parts. He was responsible for developing the largest closed die forging made up to the present time.

Ed Dixon joined ASM in 1922



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and is a past-chairman of the Milwaukee Chapter. He has been active in other technical societies, especially ASTM, ASME, SAE, SESA and API, and has served on specification-writing groups and on technical and governmental committees.



Floyd R. Anderson

FLOYD ANDERSON is a Coloradan who has been practicing metallurgy in his native state since 1925. He began as a laboratory assistant at the Denver Rock Drill Co. in his home town of Denver. Since then, that company has become Gardner-Denver Co., and Anderson has become chief metallurgist.

Anderson left Denver for a few years in the early thirties to serve as metallographist for Colorado Fuel & Iron in Pueblo, returning in 1934 to become assistant metallurgist with Gardner-Denver. He has been chief metallurgist since 1937.

Anderson has been active in the American Society for Metals since 1937. He has been chairman of the Rocky Mountain Chapter and a member of the National Nominating Committee; at present he is serving on both the Metals Handbook Committee and the ASM Committee on Tool Steel, which has contributed a detailed report on selection of tool steels in this issue.

Anderson has served on various other technical society and government advisory committees over the past fifteen years. He is a member of the American Welding Society, Society for Nondestructive Testing, and the National Association of Foremen. Although not a degree holder, he was recently elected to Tau Beta Pi at the University of



Cleaning Specialists*

* [SPECIALIST—One who devotes himself to some special branch of activity.]

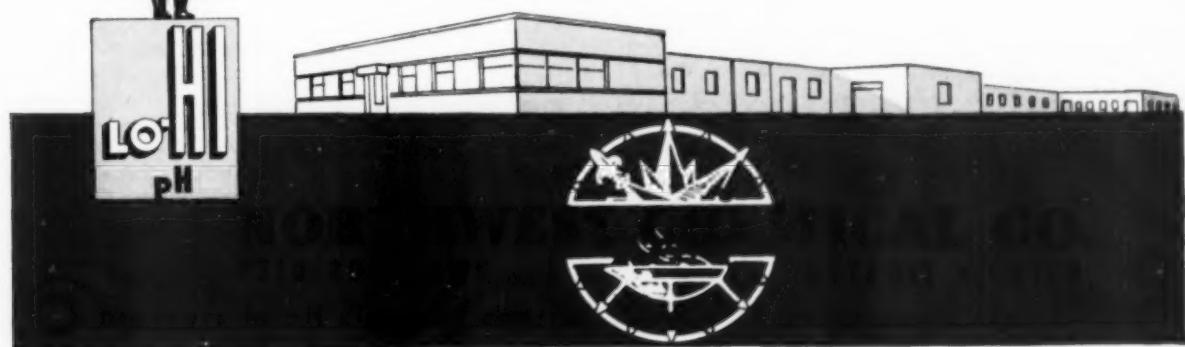
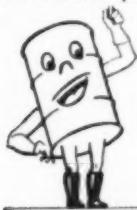
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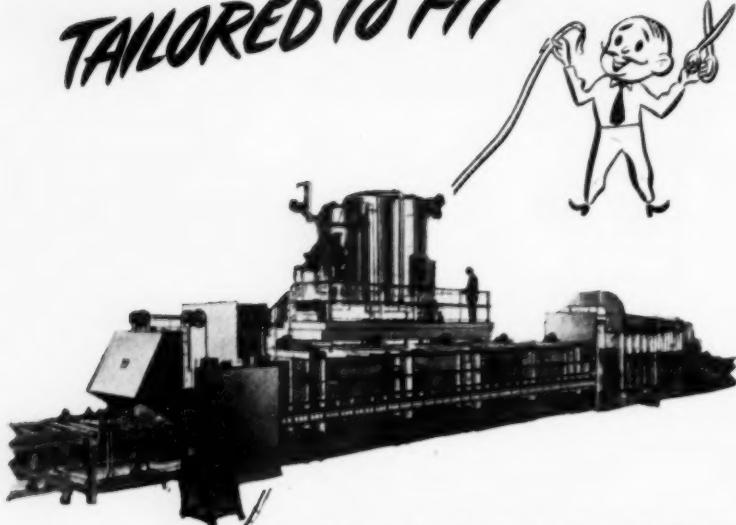
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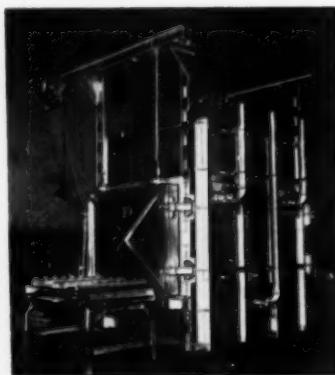
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Denver. He served in various governmental consulting projects during the second World War.



William Lawrence Badger

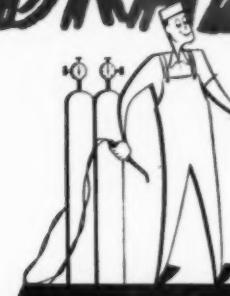
In 1926, BILL BADGER graduated from Northeastern University, went to work for General Electric Co., and joined the ASM. He was placed in charge of metallurgy in the Thomson Laboratory of General Electric in 1942 and became manager of the newly formed Small Aircraft Engine Laboratory of the company in 1954. His primary interest in all of these positions has been high-temperature metals.

Mr. Badger has been active in the Boston Chapter of ASM and was chapter chairman last year. As well as being a member of the Metals Handbook Committee, he served on the ASM Committee on Heat-Resisting Alloys for this Supplement. For a number of years he has held membership on the Heat-Resisting Materials Committee of NACA and is at present chairman of that group. He is also on the NACA Committee on Power Plants for Aircraft.

Orville E. Cullen

As chief metallurgist of Surface Combustion Corp., ORV CULLEN is close to both heat treating and steel mill practices, two subjects of major interest to ASM'ers. He has been active in the affairs of the Society for fifteen years, and a member of the Handbook Committee since 1952. He served the Toledo group as chair-

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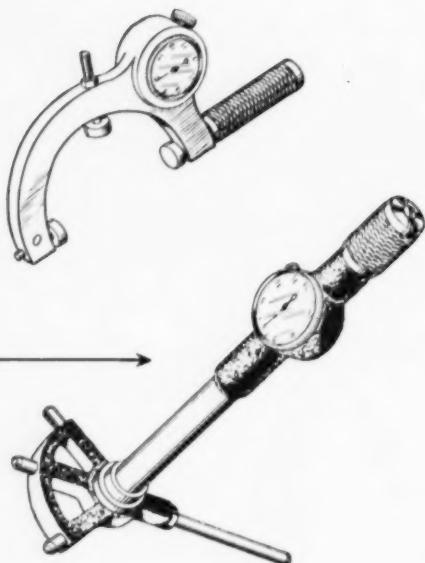
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O. E. Cullen

man in 1946, and as Secretary in 1944.

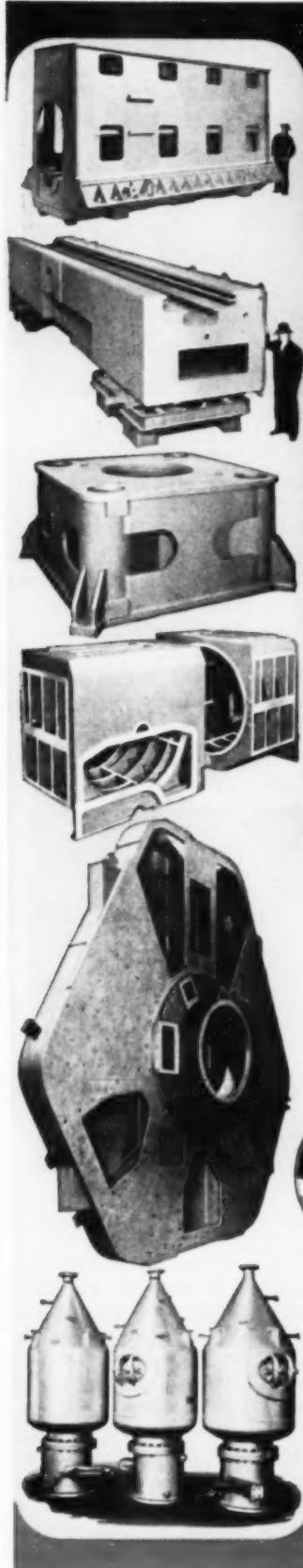
Cullen was born in Michigan, received his elementary and high school education in Toledo, and returned to Michigan to take his college training at the University of Detroit. After getting his Bachelor of Metallurgical Engineering degree in 1930, he spent six years with General Reduction Corp. in Detroit as a research engineer. In 1936, he returned to Toledo to join Surface Combustion as a research and development engineer, and was named chief metallurgist in 1942, specializing in the development and application of controlled atmospheres and heating furnaces.

For four years, beginning in 1943, Cullen found time to lecture in metallurgy at the University of Toledo evening classes, and more recently has been chairman of the ASM Toledo Chapter's educational committee.

Thomas E. Eagan

TOM EAGAN is chairman of the ASM Committee on Engine Metals, as well as being a member of the Metals Handbook Committee.

When Eagan joined Cooper-Bessemer as chief metallurgist in 1934 after several years as assistant superintendent of research at Midvale Co., he was returning to the section of his native Pennsylvania where his early schooling was gained. He also studied at Columbia University and Missouri School of Mines, being granted B.S. and Met. Engr. degrees by Missouri Mines. His first employment was with



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T. E. Eagan

Simonds Saw and Steel, at Harrison, N.J.

Eagan has been an active worker in technical societies. He is a past national director of AFS and this year received that society's Joseph S. Seaman gold medal for his work on alloy cast iron. He has been a member of ASM since 1925 and is a past-chairman of the Mahoning Valley Chapter.



Bruce W. Gonser

BRUCE GONSER has long made a specialty of the less common metals—including titanium, which is becoming more common these days. Dr. Gonser is chairman of the ASM Committee on Titanium, joint authors of the extensive section on that metal which appears in this issue.

Dr. Gonser is a technical director of Battelle Memorial Institute. A native of Indiana, he was graduated from Purdue in 1923. The next year

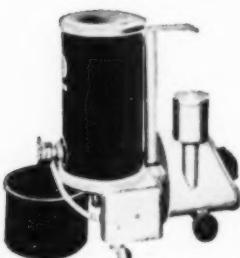
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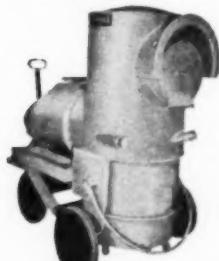
Spencer portables are made in a range of sizes from $\frac{1}{2}$ HP to 15 HP, with large capacity dirt cans arranged for easy emptying. These units have ample vacuum power for all kinds of industrial cleaning and waste removal. A complete line of heavy duty vacuum tools and attachments is available, and described in Bulletin No. 115.



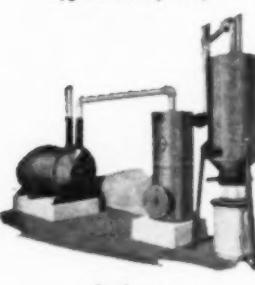
$\frac{1}{2}$ HP Commercial



$\frac{1}{2}$ HP Industrial



7/2 HP Heavy Duty



Stationary

OFFICE CLEANING

The $\frac{1}{2}$ HP illustrated, and also the $\frac{3}{4}$ and 1 HP sizes are particularly well adapted for the office end of the building. The smaller sizes are light enough to be carried up and down stairs, and all have sufficient power for fast and thorough cleaning. Bulletin 114.

INDUSTRIAL CLEANING

The $\frac{1}{2}$ HP unit also shown has sufficient power for the industrial end of an average plant. For large litter, or heavy duty cleaning, the $\frac{7}{2}$ HP unit may be used with two operators working at the same time. Bulletins 102 and 112.

Stationary Systems are available up to 100 HP and described in Bulletin No. 125.

Gasoline engine driven units and various combinations for water pick up are also available.

SPECIAL APPLICATIONS

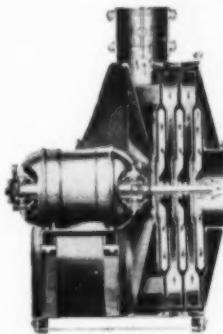
In addition to regular floor and overhead cleaning, more than 100 special applications for vacuum are described in Spencer Bulletin No. 144. Also, bulletins are available on the following subjects:

Boilers Boiler efficiency is increased by removing soot from boiler tubes. Bulletin No. 137.

Drill-Vac A hood is connected to rock drills, removing dust hazards and increasing drilling speeds. Bulletin No. 111.

Sump-Vac Liquids are removed from sump tanks in minutes instead of hours. Bulletin No. 130.

Conveyors Pneumatic conveying of bulk material or tube systems — either by vacuum or pressure blowing. Bulletin No. 143, and Bulletin No. 104.

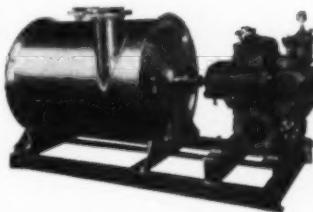


TURBO-COMPRESSORS (Blowers)

Spencer Turbos are built in sizes from 85 to 20,000 c.f.m. and from four ounces to ten pounds pressure. They are distinguished by the simple, all metal construction, light weight impellers, wide clearances and long life characteristics.

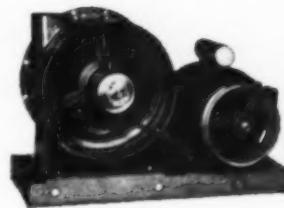
GAS BOOSTERS

Spencer Gas Boosters are available for all conditions in gas operation and for handling various kinds of acid fumes, poisonous, corrosive or explosive gases. Bulletin No. 126.



DIRECT DRIVEN

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APPLICATIONS

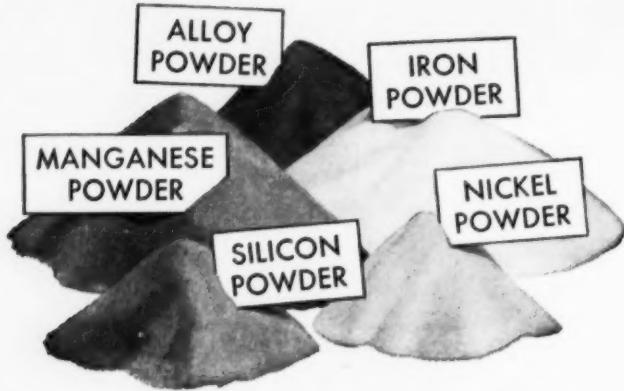
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he earned a M.S. at the University of Utah and started a tour of employment with American Smelting and Refining Co. which took him to six different states. This was followed by graduate study and a D.Sc. degree at Harvard. Conser also worked in metallurgical research with Superior Zinc Corp. and National Radiator Corp. before joining the Battelle staff in 1934.

He has been a member of ASM since 1936, and is a past-treasurer of the Columbus Chapter and member of the present Metals Handbook Committee. He has appeared as a speaker before some 35 ASM groups during the past ten years.



Max A. K. Hansen

MAX HANSEN came to this country from his native Germany in 1947 to become associated with the Illinois Institute of Technology. He is at present consultant to the Institute's Armour Research Foundation.

Dr. Hansen, a member of the Metals Handbook Committee since 1949, is the author of the well known compendium of phase diagrams, "The Constitution of Binary Alloys", published in Germany in 1936. He received his doctorate from the University of Göttingen, in 1924, at Tammann's Institute. For many years he was simultaneously associated with the Technical Institute of Berlin and the Duerener Metallwerke A.G., of that same city. Dr. Hansen rose to be vice president of Duerener and was professor and head of metallurgy at the Technical Institute when he came to the U.S. He was also associated with the Kaiser Wilhelm Institute for Metal Research in Ber-



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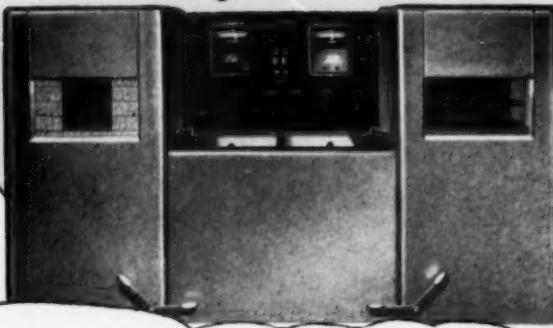
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lin as head of the metallurgy department, and I. G. Farbenindustrie, in magnesium research, during his early professional career.



N. E. Promisel

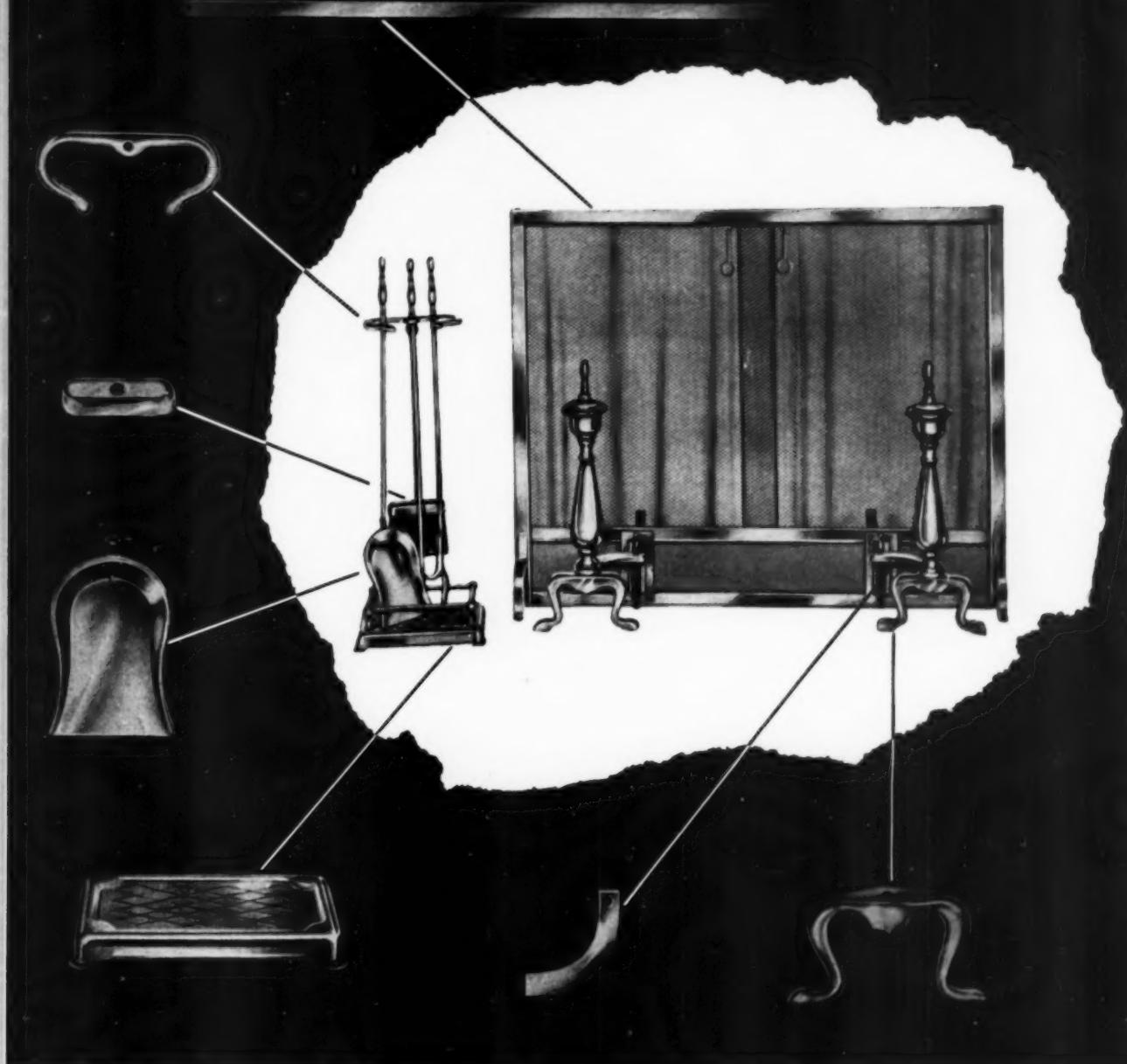
NATE PROMISEL, chief metallurgist and head of the materials branch of the U. S. Navy Bureau of Aeronautics, has contributed to this issue in three ways—as chairman of the Committee on Magnesium, member of the Committee on Titanium, and member of the Metals Handbook Committee.

Mr. Promisel is a native of Massachusetts; he received B.S. and M.S. degrees in electrochemical engineering from M.I.T. in 1929 and 1930, and joined International Silver Co. as a research electrochemist in 1930, later becoming assistant director of research. He left that company in 1940 to engage in private consulting work in metallurgy, electrochemistry and metal finishing.

With the outbreak of the war, Promisel accepted a position with the Navy, taking charge of several metallurgical programs of the Bureau of Aeronautics. He moved into his present position in 1948, and now has responsibility for a diversity of research, development, control and specification activities.

Robert Sergeson

BOB SERGESON has been continuously employed in the steel industry since his graduation from the University of Pennsylvania in 1922. Now chief metallurgical engineer of



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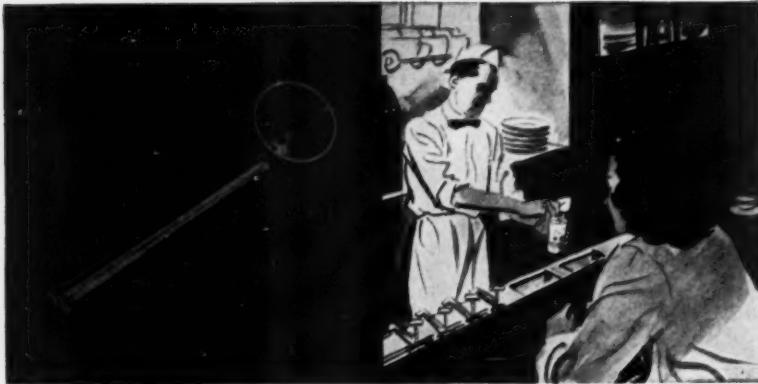
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Robert Sergeson

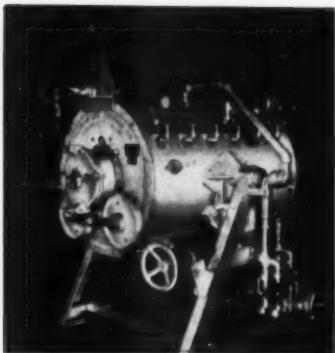
Rotary Electric Steel Co., in Detroit, Sergeson began his career with the old Central Steel Co. in Massillon, Ohio, immediately after receiving his B.S. in chemical engineering. By the early thirties, the company had become Republic Steel Corp., and Sergeson, having worked in various operating departments in the meantime, was in charge of the metallurgical laboratory. He joined Crucible Steel in 1938 as chief metallurgist of the Park Works in Pittsburgh, and became chief metallurgical engineer of Rotary Electric in 1945.

Sergeson has been an ASM member for 30 years. He was chairman of the Canton-Massillon Chapter in 1932-33, a member of the ASM Advisory Committee on Navy Diesels in 1951 and of the ASM Metals Handbook Committee since 1952.



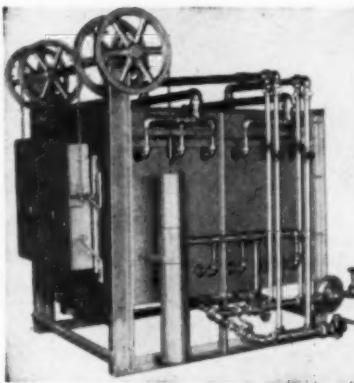
L. E. Simon

LARRY SIMON is another triple-threat man on the Handbook team. Chief metallurgist of Electro-Motive



ROTARY BATCH CARBURIZERS

The Batch Type furnace (shown above) is highly flexible in that it can handle atmosphere or general work in independent charges for hardening, annealing, and normalizing of metal products, also calcining and roasting of paint pigments, drying or burning abrasives and oxide reduction. Extremely economical, the various sizes of this rotary furnace are adaptable to almost any work where absolute uniformity is essential.



The originators of much of the industrial gas controlled atmosphere equipment in use today, AGF engineers and metallurgists are well qualified to recommend the proper equipment for your purpose. A few of the more popular types of furnaces are illustrated and described.

OVEN TYPE FURNACES

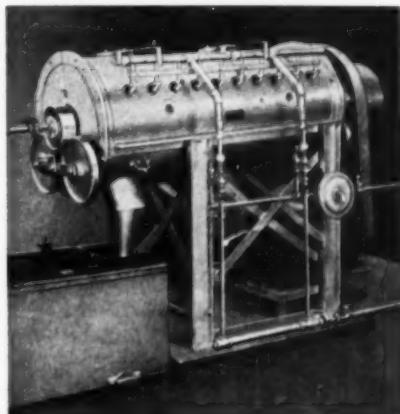
The large oven type furnace (shown at the left) is used for annealing, hardening, carburizing and a wide range of controlled temperature work from 1300 to 1800° F. Special Oven Type furnaces can be had for temperatures up to 2500°. The liberal placing of independently operated burners in AGF Oven Type Furnaces makes them models of low gas consumption and efficiency.

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BLOWPIPES
BURNERS
BURNER TIPS
CARBURIZERS
DISSOCIATORS
FIRE: CROSS, GLASS, HAND
FLOW METERS
FORGES
FURNACES: ANNEALING
 ATMOSPHERE
 AUTOMATIC
 BRAZING
 CYLINDRICAL
 MUFFLE
 OVEN, POT
 RECIPROCATING
 ROTARY SALT-BATH, TUBE
 VERTICAL
HEATERS: SOLDERING IRON, RIVET
MACHINES: HEATING,
 AUTOMATIC HEAT TREATING,
 QUENCHING
 ROLLER HEARTH
MELTERS
MIXERS
PRESSURE GAUGES
RATIO SETS
TORCHES
ZERO GOVERNORS
 AND MANY OTHER
 PARTS AND ACCESSORIES

CONTINUOUS ROTARY HEATING MACHINES and CARBURIZERS

The rotary type of Continuous Clean Hardening Furnaces have the special feature of mixing the work as they automatically advance it through the retort thus assuring uniform heating of all the work. Used for uniform carburizing, clean hardening, annealing and other heat treating, these Rotary Retort Furnaces are equipped with automatic controls for variable temperatures and heating time cycles.



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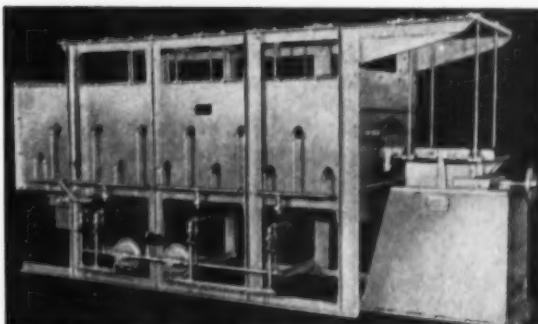
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Div. of General Motors, Simon is not only a member of the ASM Handbook Committee but also of the Committee on Carbon and Alloy Steels and the Committee on Heat Treatment, both of which contributed articles to this issue.

Simon went to work in the General Motors Research Laboratories in 1937 with a B.S. degree from the University of Wisconsin. Four years later he transferred to the Electro-Motive Div. as heat treat superintendent and in 1942 became chief metallurgist.

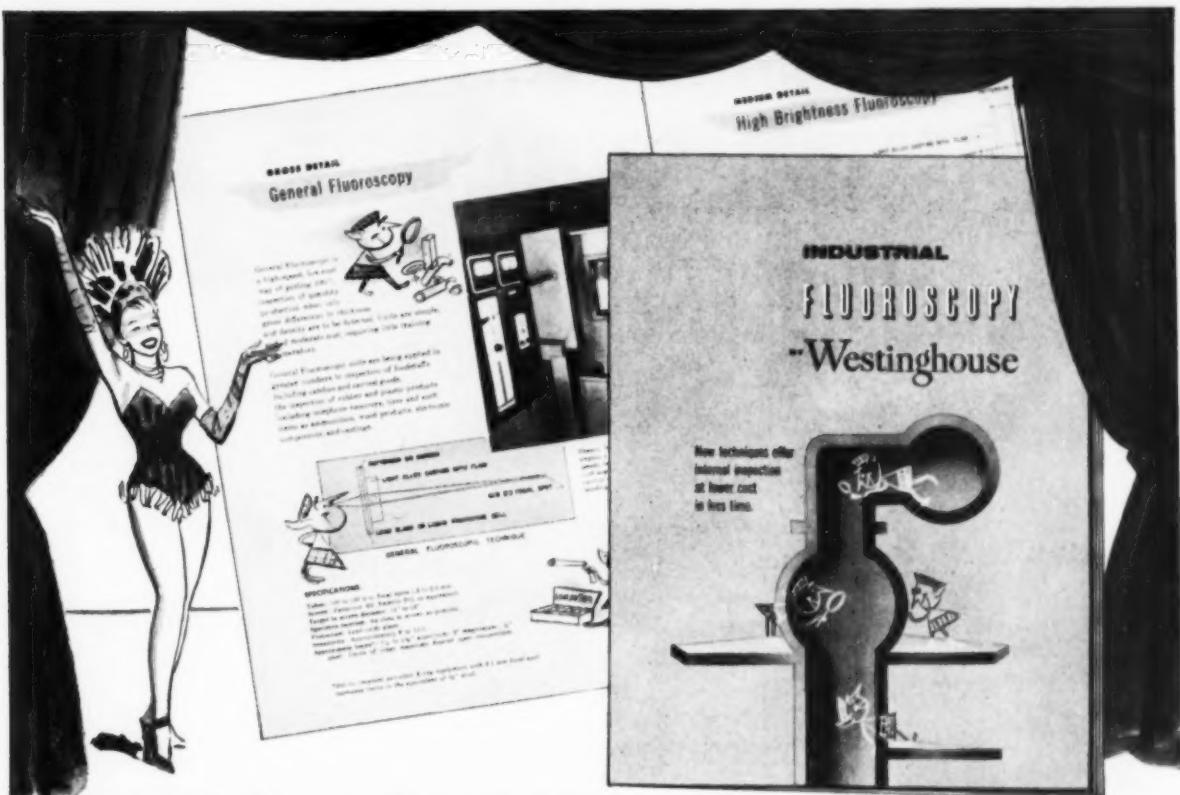
Simon is a past-chairman of the Chicago Chapter of ASM, a member of the ASM Publications Committee, and served on the Society's Advisory Committee on Naval Gun Mounts. He is also active in committee work of the SAE and was a member of the Metallurgical Advisory Board Panel on Boron Steel, for the National Research Council.



Stephen F. Urban

One of several winners of the Henry Marion Howe Medal of ASM who have participated in the recent Handbook activity is STEVE URBAN, director of research, Titanium Alloy Manufacturing Div., National Lead Co.

A native of Detroit, Dr. Urban is a product of the University of Michigan, where he received his doctorate in 1933. After completing his graduate work, he joined National Tube Div. of U.S. Steel as a research metallurgist. Two years later he was transferred to the Research Laboratory at Kearny for a year before



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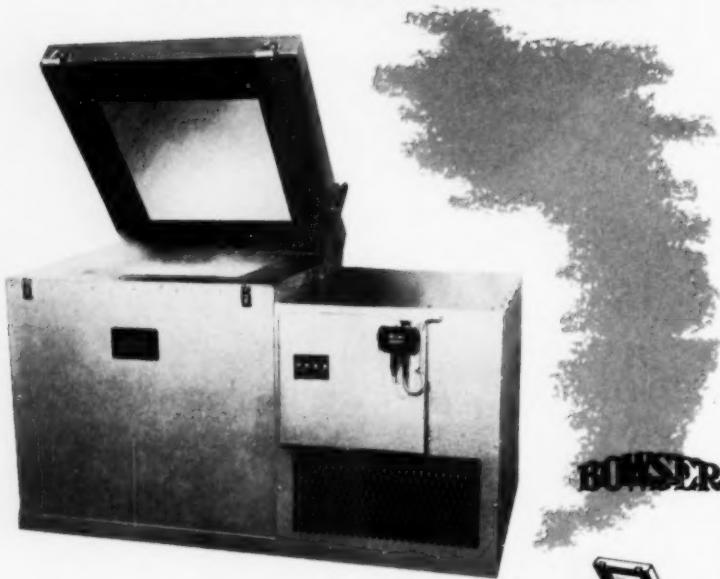
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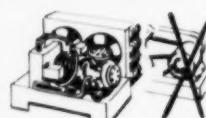


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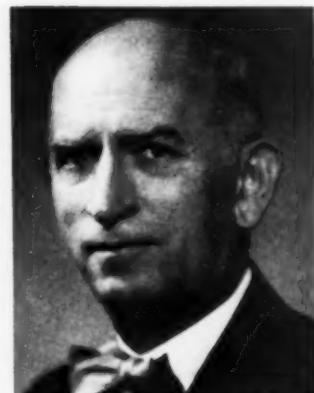
Semi-hermetic compressors reduce bulk, insure trouble-free operation.



Fan and coil arrangement permits air circulation within the chamber.

going to South Works to be in charge of metallurgical research. In 1945, he assumed his present position with Titanium Alloy Manufacturing.

Dr. Urban has been a member of ASM since 1928 and has served on the executive committees of both the Chicago and Buffalo Chapters. He is a member of the National Nominating Committee and the Metals Handbook Committee at the present time.



L. H. Winkler

L. H. WINKLER brings to the ASM Metals Handbook Committee nearly half a century of experience in the steel industry. He received his B.S. degree from the University of Missouri in 1907 and that same year was employed by Cambria Steel Co., at Johnstown, Pa., as a mechanical engineer. Winkler was in charge of the metallurgical department at Cambria when the company was acquired by Bethlehem Steel. In 1929, he was transferred to the office of the operating vice president of the company in Bethlehem, Pa., where he continues to serve today.

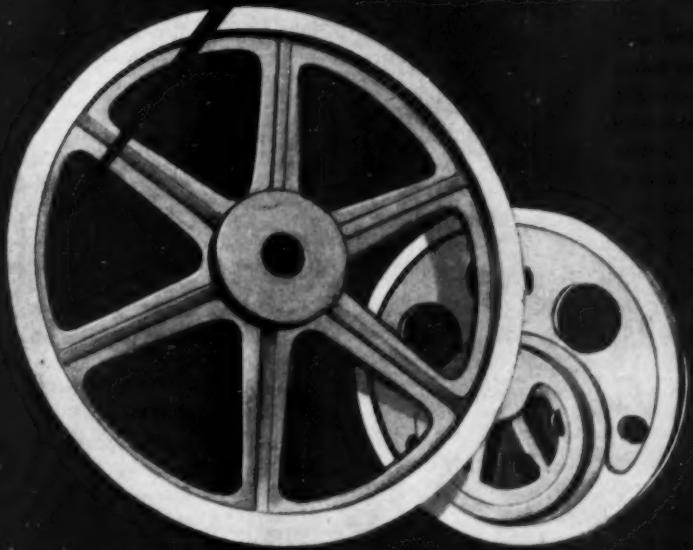
His membership in the American Society for Metals began in 1928.

Hyman Bornstein

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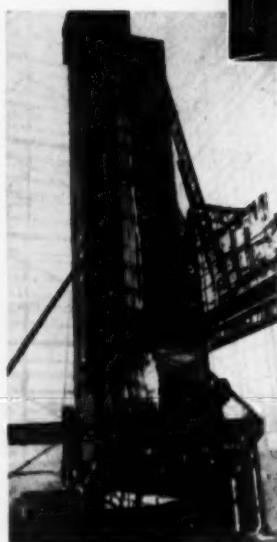
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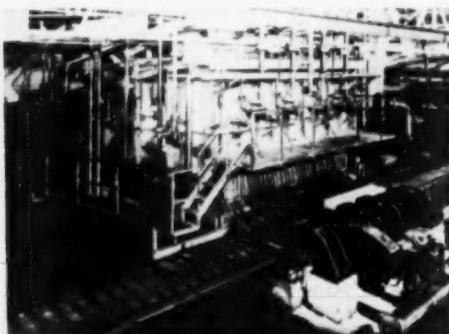
Car type, recirculating furnaces for annealing steel castings and forgings.



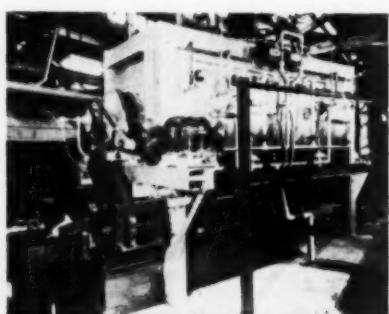
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Hyman Bornstein

country. He is a past-president of AFS and in 1947 received that Society's William H. McFadden Gold Medal. He retired from Deere & Co. in 1953 to become a consulting metallurgist in Moline, Ill., and continue many of his activities in the service of technical societies, being currently chairman of the AFS Cast Metals Handbook Committee and chairman of the ASM Committee on Cast Metals.

A graduate of Armour Institute of Technology in chemical engineering (1911), Bornstein also holds an LL.B. degree from John Marshall Law School (1915). He has been a member of ASM since 1920, is a past-trustee and a past-chairman of the Tri-City Chapter. In ASTM, he was chairman of Committee A-3 on Cast Iron for six years. He served as chairman of the Iron and Steel Technical Committee of SAE and is chairman of the Joint Committee on Definitions of Heat Treating Terms.

In the first World War, he was a Captain in Army Ordnance. During the second war, he served on the Iron and Steel Committee of the War Engineering Board and was chairman of one of the Army Ordnance industrial integration committees.

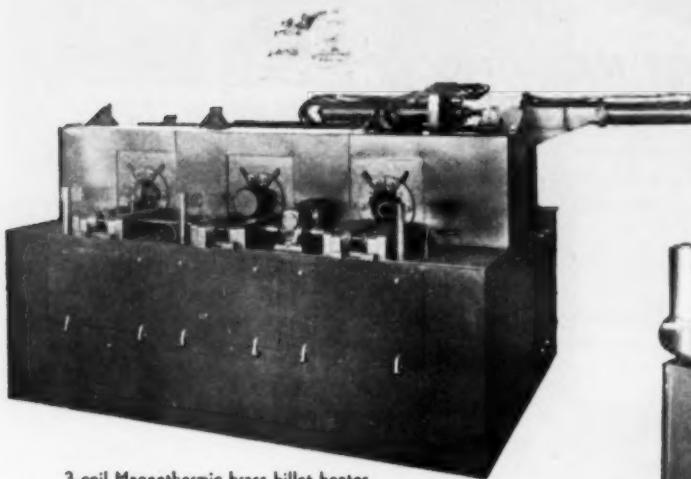
Howard C. Cross

The metallurgical career of Howard C. Cross began in 1921, at the National Bureau of Standards, six years before he received his B.S. degree in chemical engineering from George Washington University.

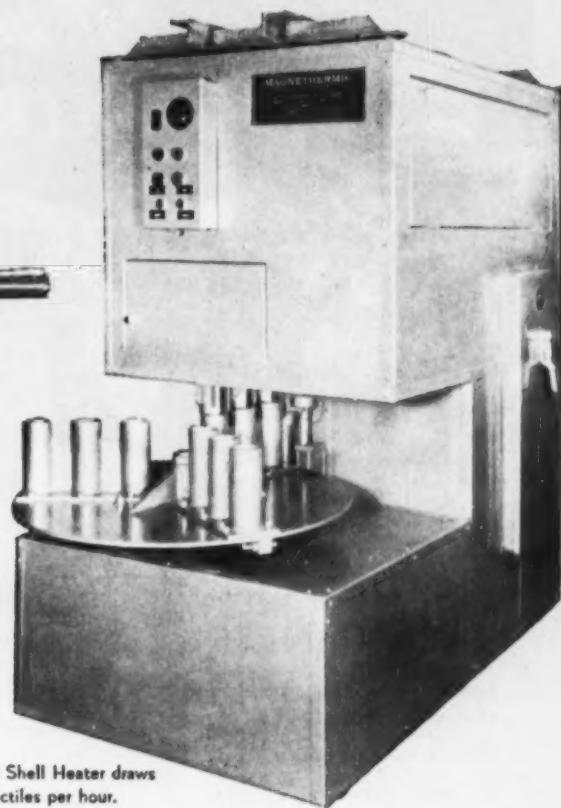
A native of Washington, D.C., Cross continued with the Bureau un-

Why, Where, How and Wherethose...

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3-coil Magnethermic brass billet heater
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HERE'S THE WHERE

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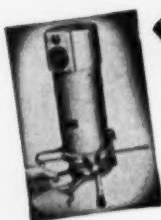


Your inquiry . . .

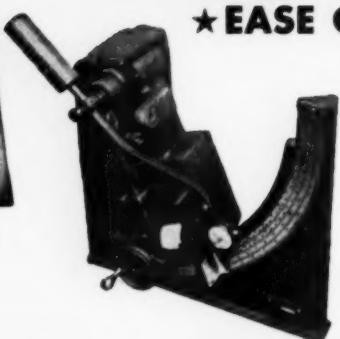
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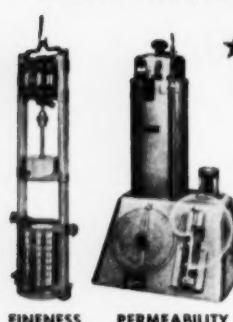
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AND DEFORMATION

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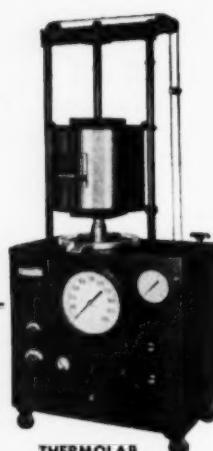
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Howard Cross

til 1929, when he joined the staff of Battelle Memorial Institute. He is now assistant coordination director at Battelle, where he has worked intensively in his special field of high-temperature metals.

Howard Cross is chairman of the ASM Committee on Heat-Resisting Alloys and for the 1948 Handbook was chairman of the committee that wrote on heat-resisting castings. He has been chairman of the Columbus Chapter of ASM, and a member of the society since 1923.

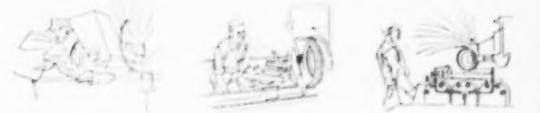


Hans Ernst

HANS ERNST, director of research for Cincinnati Milling Machine Co., has been in charge of development and research there during the past 28 years. His outstanding laboratory has done much fundamental research in machining and has been the training ground for several engineers who are now among the leaders in metal-cutting research.



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LEARNED A LOT
ABOUT
TITANIUM
SINCE 1949



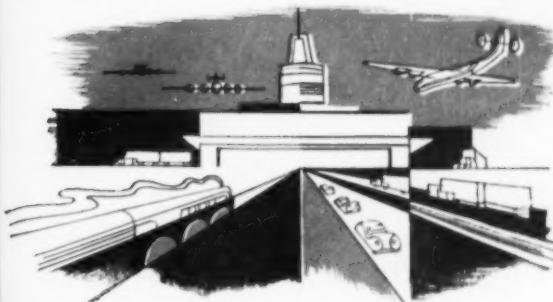
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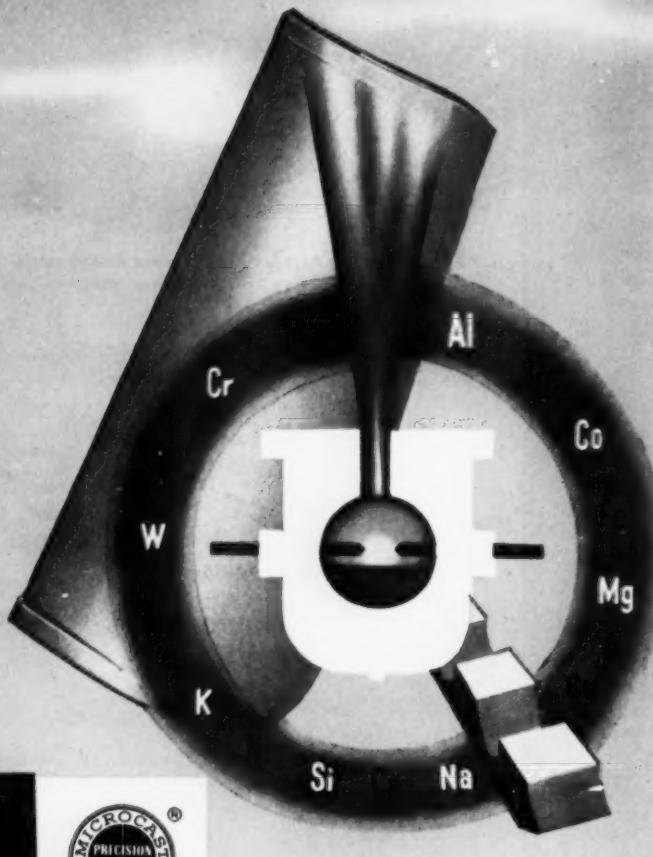
today The use of the "wonder metal" is largely restricted to aircraft use. American Welding annually produces thousands of Titanium rings for jet engines.



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Ernst is a native of Australia, where he was graduated from Melbourne Technical College and began his engineering career before coming to the United States in 1915.

He served with the Royal Air Force of Canada during the first World War, and was associated for eight years thereafter with the Western Cartridge Co., in research and machine development work connected with the manufacture of ammunition and sheet metal specialties, before taking his present position in the laboratory of Cincinnati Milling Machine Co., in 1926.

Hans Ernst is a fellow of the ASME, a member of ASM (since 1923), the New York Academy of Sciences, Sigma Xi, and ASTE, and is a past-president of the Engineering Society of Cincinnati.

He is chairman of the ASM Committee on Machining.



Richard A. Flinn

DICK FLINN, chairman of the ASM Committee on Nodular Iron, is a versatile foundryman—he has made castings in industry, in the university and on TV.

In industry he held metallurgical positions with International Nickel (1937 to 1940) and with American Brake Shoe (1941 to 1951).

In the University of Michigan, he is professor of metallurgy and production engineering, and directs the Cast Metals Laboratory.

On TV, he and half his class went on a state-wide TV educational program recently to show all Michiganders how castings are made.

Dick Flinn took his undergraduate degree in chemical engineering



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99 PARK AVE., NEW YORK 16, N. Y.

at the College of the City of New York (1936) and his doctorate in metallurgy from M.I.T. (1941). He received the Henry Marion Howe Medal of ASM in 1944 and the Peter L. Simpson Memorial Gold Medal of AFS in 1947. He is co-inventor of a steel railroad wheel and has recently devised a new micro-bend tester for observation of localized flow of metal under load. He is a ten-year member of ASM.



Russell Franks

Stainless steel use has nearly doubled since the 1948 edition of the Metals Handbook was published. RUSSELL FRANKS is chairman of the ASM Committee on Stainless Steel which keeps the Handbook and its readers abreast of this growth.

On graduation from Virginia Polytechnic Institute in 1921, with a B.S. degree in chemical engineering, Franks joined the staff of Union Carbide and Carbon Research Laboratories at Niagara Falls, and has been interested almost exclusively in stainless and heat-resisting steels ever since.

From 1921 to 1946 he investigated chromium metal and chromium steels, took part in the development of the nickel-base Hastelloys, developed several wrought high-temperature alloys for gas turbines, and served as chief metallurgist of the Laboratories during the early 1940's.

Since 1946, Franks has been with Electro Metallurgical Co., another Union Carbide division, and at present is manager of technical services and development.

Russell Franks co-authored "Alloys of Iron and Chromium", one of

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the Engineering Foundation monographs on alloys of iron. In 1950 he was awarded the Henry Marion Howe medal of ASM for his part in developing the extra-low-carbon 18-8 stainless steels.

Franks served as Chief of the Super-Alloys Branch of the War Production Board in the second World War, and is a member of the NACA Committee on Heat-Resisting Materials. His membership in ASM started in 1934.



W. R. Frazer

Tool steel and its heat treatment have been featured in every edition of the Metals Handbook. The Committee on Tool Steel was among the first formed when the Handbook work began in 1923, and BILL FRAZER, present chairman of that Committee, began accumulating experience on tool steels the same year, when he joined Halcomb Steel as assistant metallurgist. Later he was night superintendent in the Halcomb mill; in 1929 he accepted the position of chief metallurgist of Eclipse Aviation Div. of Bendix; and in 1935 became chief metallurgist of Union Twist Drill Co., the position he holds today.

A native of Michigan, Frazer received his B.S. degree in chemical engineering at the University of Michigan in 1921, and his Sc.D. in metallurgy at M.I.T. in 1923.

Dr. Frazer has been an ASMer since 1924. He is one of the select group of members who have been chairman of more than one chapter — Syracuse in 1928 and New Jersey in 1933. He is presently a member of the Springfield Chapter. He pre-

Why Alloy Steels?



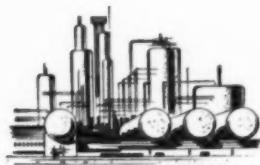
Carbon steels are better today than ever before. A major producer of both carbon and alloy steels, Republic is aware of this fact. Even so, there are limits to the application of carbon steels. Machine design may restrict the size of a part. High strength may be an essential combination with light weight. Sometimes surface hardness and ductility must be held within the limits. Such are the applications in which *only* alloy steels can perform definite tasks with certainty of results at lower ultimate cost.



Take large sections—where hardness must be carried deep into the steel. Heavy crankshafts, connecting rods, piston rods, large gear and axles are examples. Here alloy steels *are necessary*, and the cost low in proportion to results. With carbon held constant, depth-hardening quality increases as the alloy content is increased.



Sometimes weight and space limitations demand that smaller sections carry heavier loads safely. For safety's sake, the answer *must be* alloy steels. Under repeated stress, high tensile strength and hardness do not necessarily indicate high fatigue properties. The load-carrying ability of a steel depends upon its alloy constituents and the form of the structure at the time it is bearing the load.



A problem of high pressures at elevated temperatures may present a problem. But alloy steels *have proved* their high resistance to creep. Some stainless alloys maintain high strength up to 1800° F. They resist oxidation—therefore do not lose their strength appreciably through reduction of section.



High elastic properties and strength may be the primary requirement, especially for welded structures. Weight reduction may be most important. In these applications, low carbon complex alloy steels *offer distinct advantages*. Such alloy steels at equal or higher yield points show low weld-hardening tendencies. Resistance to corrosion is improved. So is ductility of the weld. And retention of toughness at sub-zero temperatures, as well as creep resistance at high temperatures, is better.



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sented the first series of educational lectures given at the Syracuse Chapter, and has served on the ASM National Nominating Committee.



M. L. Frey

MUIR FREY's most recent contribution to the educational work of ASM has been made in his role as chairman of the Committee on Carbon and Alloy Steels, which is responsible for the opening article of this issue.

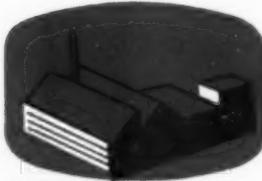
Frey, assistant to the general works manager, Tractor Mfg. Div., Allis-Chalmers Mfg. Co., received B.S. and M.S. degrees in metallurgy from the Missouri School of Mines in 1923. His engineering and metallurgical experience includes ten years as chief metallurgist for John Deere Tractor Co., Waterloo, Iowa, four years as service metallurgist for Republic Steel, six years as chief metallurgist, Aircraft Engine Div., Packard Motor Car Co., and ten years in his present position, which involves staff supervision of metallurgy, welding and metal finishing throughout the Tractor Manufacturing Div. of Allis-Chalmers.

His ASM educational activities include a series of lectures sponsored by the Chicago Chapter last year in memory of Marcus A. Grossmann, articles in the publications of ASM, membership on the Metal Progress Advisory Board, chairmanship of the Committee on Heat Treatment of Carbon Steels, which has contributed to the last two editions of the Metals Handbook, and membership on the ASM Advisory Committee on Naval Gun Mounts.

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Frey has served as chairman of the Milwaukee Chapter and vice-chairman of the Detroit Chapter. He has also been chairman of the SAE Iron and Steel Executive Committee, the SAE Tractor and Earth Moving Group (Panel D), and the Detroit section of AIME.



T. A. Frischman

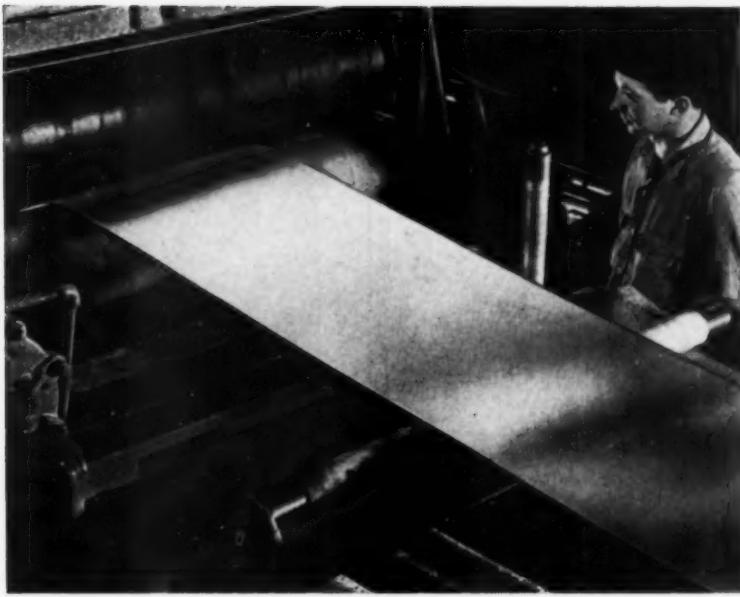
TOM FRISCHMAN, in his eighteenth year as chief metallurgist for the Axle Div. of Eaton Mfg. Co., in Cleveland, is chairman of the ASM Committee on Heat Treating. This committee has prepared three articles for this issue, including one on the cost of heat treating.

Frischman began his career at National Tube Co., after graduating from Case School of Applied Science with a B.S. in metallurgy in 1925. He was with Eastern Rolling Mill Co. of Baltimore for one year and Timken Steel and Tube for eight years before accepting his present position at Eaton in 1937.

Frischman has been an ASM member for more than 25 years and an officer of the Cleveland Chapter. He is also active in SAE and ASTM.

J. B. Johnson

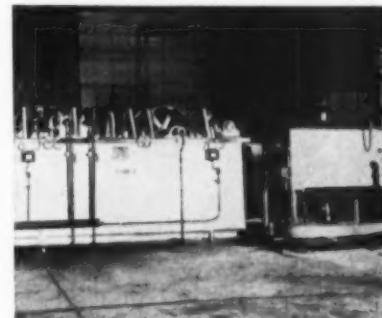
J. B. JOHNSON is chief scientist of the Aeronautical Research Laboratory of the Air Force at Wright-Patterson Air Force Base, Dayton. His several titles during 38 years with the Air Force and its predecessor organizations may all be fairly summarized as "in charge of metals and



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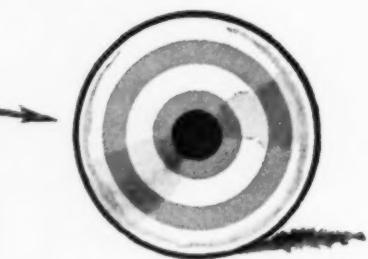
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metallurgy". The metals he knows best are aluminum, magnesium, titanium, heat-resisting alloys and alloy steel. He is chairman of the ASM Committee on Aluminum which contributed a report on applications to this issue.

J. B. was a member of the Metals Handbook Committee from 1944 to 1951, and chairman from 1948 to 1951. A member of the Society since 1927, he has served a term as National Trustee.

J. B. was born in Olean, N.Y., and graduated from Cornell in mechanical engineering. He worked for a railroad for a year or two before joining the Aviation Section of the Signal Corps in 1916.



George L. Kehl

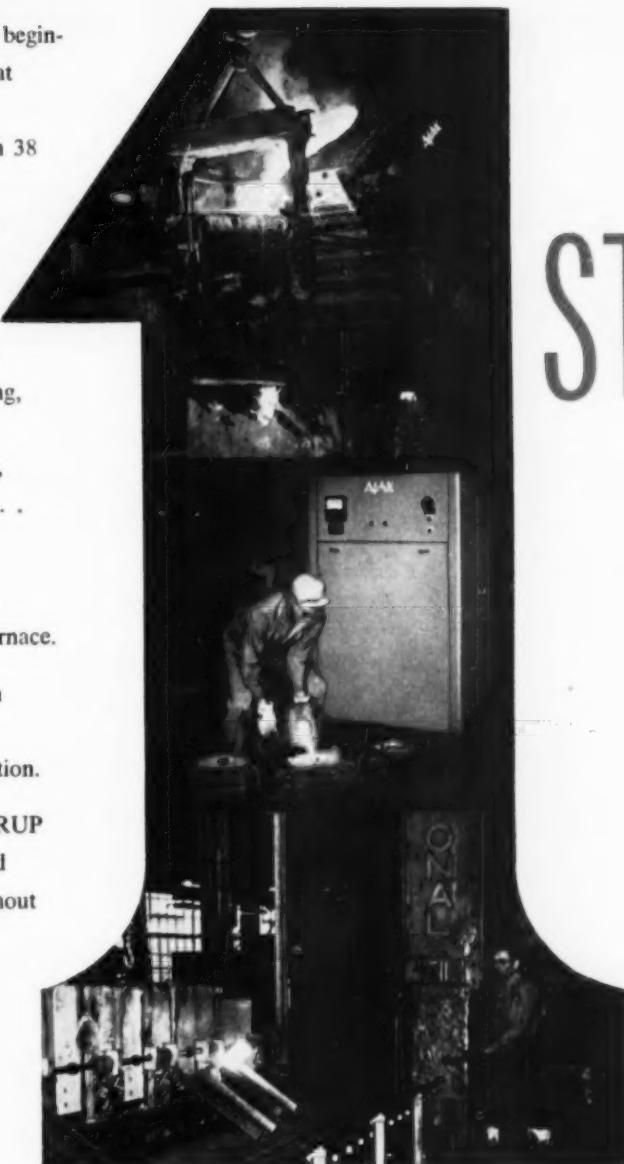
GEORGE KEHL, associate professor of metallurgy at Columbia University, is chairman of the ASM Committee on Metallography.

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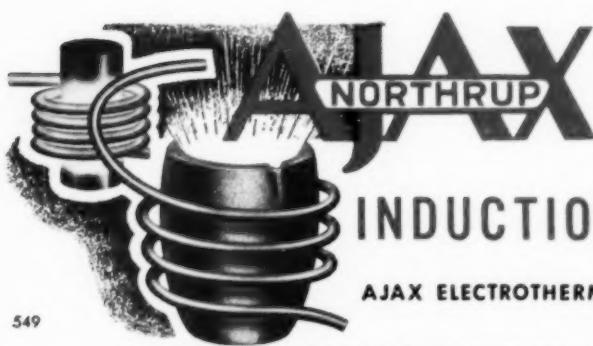
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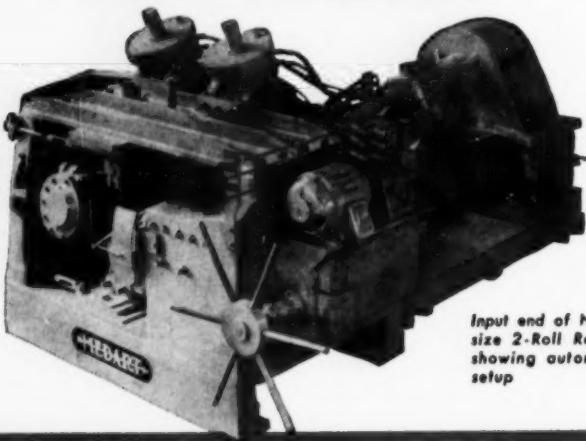
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A graduate of the University of Wisconsin in chemical engineering, Kehl received his M.S. in metallurgy at Lehigh and was assistant professor of metallurgy there for two years before joining U. S. Steel as a research metallurgist in 1939. In 1942, he became a member of the faculty of Columbia; this affiliation has continued except for a three-year leave of absence during which he was group leader of the metallography and heat treating divisions of the Los Alamos atomic bomb project. At present, Kehl is a consultant to Argonne National Laboratory and director of three Government research projects at Columbia.

Kehl's book, "Principles of Metallographic Laboratory Practice", now in its third edition, is one of the best known metallurgical textbooks. He has been a member of ASM since 1941, and is currently chairman of the educational committee of the New York Chapter.



Jack E. LaBelle

JACK LABELLE, chief metallurgist of the Detroit Diesel Engine Div. of General Motors, has devoted most of his professional career to the phase of engineering dealing with selection and processing of metals for automotive engines. He is chairman of the ASM Committee on Shot Peening which wrote on that process and other methods of surface working in this issue.

LaBelle is a native of Michigan and attended public schools in Flint. He received his B.S. degree in chemical engineering from Michigan State in 1937.

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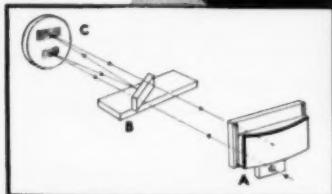
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1937 as a chemist. He changed to metallurgy in 1938, and in 1941 became assistant chief metallurgist of the Division. During the war, he served as an officer in the U.S. Army in the European theater of operations. Following his release from the Army, he was promoted to chief metallurgist in 1951.

LaBelle has been a member of ASM since 1938 and has been active on several committees of the Detroit Chapter.



Robert Howland Leach

ROBERT H. LEACH has been the chairman of each Metals Handbook Brazing Committee since this subject first appeared in 1936. He was born in Brockton, Mass., in 1878, which makes him ASM's senior chairman.

After graduating from M.I.T. in 1900, he became superintendent of a silver-lead mine in Idaho and, later, of a gold chlorination mill in South Dakota, followed by similar positions in Michigan. He was manager of the Britannia Mining Co. in 1909, becoming its vice president and managing director in 1910.

He joined Handy and Harman in 1914, where he has been successively superintendent, assistant manager, manager, vice president of production and research, vice chairman of the executive committee and, since 1952, director and technical consultant.

His special interests have been (and still are) the melting and processing of precious metals and development of new precious-metal alloys for many industrial applications.

R. H. Leach has been a member



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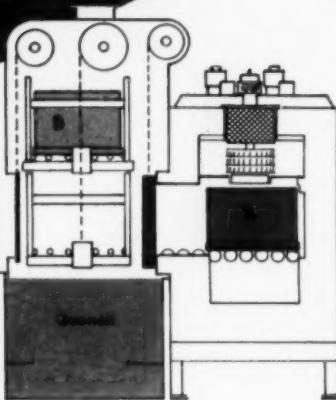
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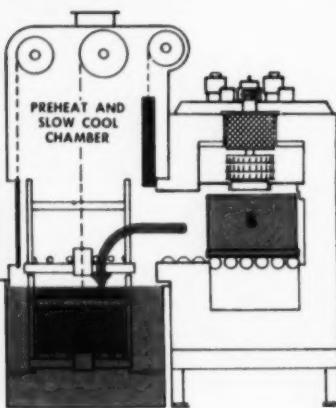
1-LOADING CYCLE

Box A containing full furnace load of parts processing in work chamber. Box B—fully loaded, pre-heats in the upper vestibule. Box C—fully-loaded, waits on conveyor.



2-QUENCHING CYCLE

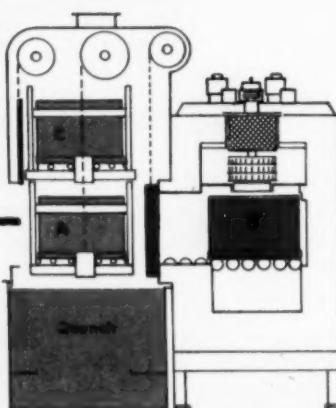
Box A completely processed, moves out to elevator and is lowered into quench; bringing pre-heated Box B to loading level. Box B is pushed into heat chamber and door is closed.



3-RELOADING CYCLE

After proper interval, outer door is opened. Box C is placed on upper elevator and raised to pre-heat position as Box A is lifted from quench and removed from lower elevator.

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of ASM since 1934 and also holds membership in ACS, AIME, ASTM, AWS and the British Institute of Metals.



George V. Luerssen

GEORGE LUERSSEN, vice president in charge of metallurgy for The Carpenter Steel Co., has been chairman of the ASM Committee on Steel Melting since 1933. For the 1939 Handbook, he was also chairman of the Tool Steel Committee and from 1943 to 1947 was chairman of the Metals Handbook Committee which directed preparation of the 1948 edition of the Handbook.

George Luerssen grew up in Reading, Pa., and went to work for The Carpenter Steel Co. there in 1907. Except for two worthy leaves of absence—1911 to 1915 to gain a B.S. at Penn State and 1917 to 1919 for military service—he has remained at Carpenter ever since, advancing steadily to his present position.

Luerssen joined the ASM in 1923, was chairman of the Lehigh Valley Chapter in 1930, and was the first recipient of the McFarland Award of the Penn State Chapter.

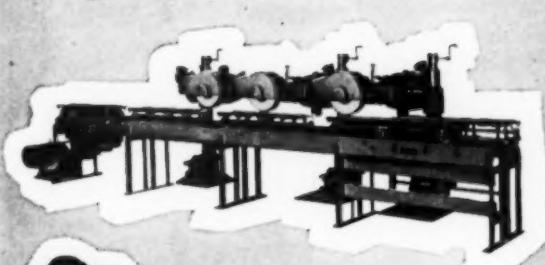
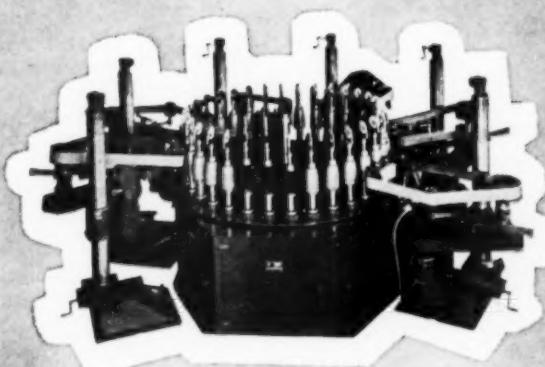
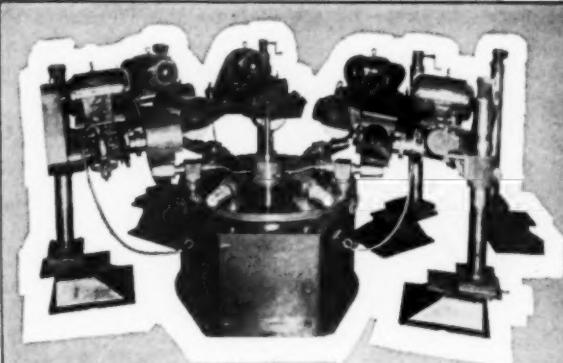
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D. M. McCutcheon

scientific staff of the Ford Motor Co. in Detroit, has been a consultant in engineering physics at Madeira Beach, Florida, since 1952.

A native Detroiter, McCutcheon received his technical education at the University of Michigan—B.S. in chemical engineering (1931) and M.S. in metallurgical engineering (1932). He has been active in ASM since 1930, was chairman of the Detroit Chapter in 1950, and is chairman of the Committee on Non-destructive Inspection which contributed to this issue.

McCutcheon was president of the Society for Nondestructive Testing in 1948. He has served as chairman of several SAE and ASTM committees and of the Detroit Council of the ASTM.



Braly S. Myers

BRALY MYERS, chairman of the ASM Committee on Metal Cleaning, is a native of Tennessee, studied



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metallurgy at Vanderbilt (B.S., 1933), and chemistry at Peabody College (M.S., 1934). In 1936 he became head of the Department of Chemistry at Northwest College, Senatobia, Miss.

Myers joined Vultee Aircraft as a process engineer in 1940. From 1941 to 1943, he was in charge of the technical laboratories of the Nashville Div. of Consolidated Vultee. During 1943, he became chief metallurgist of one of the plants of the Reynolds Metals Co., in Louisville.

From 1944 to 1947 he was assistant chief metallurgist of the Aircraft Parts Div. of Reynolds.

Myers joined International Harvester, in Chicago, in 1947, and has had a variety of metallurgical and chemical research projects under his supervision, such as tool steel research and the substitution of molybdenum for tungsten tool steel. Currently, he is in charge of the electroplating, surface preparation and inorganic chemical laboratories of the metallurgical research section.

Myers has been a member of ASM since 1943 and has been chairman of three committees of the Chicago Chapter.



Raymond C. W. Peterson

RAY PETERSON was born in DeKalb, the "corn town" of Illinois, but this has not adversely affected his formidable humor, which can settle a point of discussion with finality.

Ray Peterson is president and chief engineer of Peterson Engineering Co., of Toledo, and is chairman of the ASM Committee on Forming of Sheet Steel. He learned the die maker's trade at the City Machine and Tool Co., Toledo, starting there in 1930. In 1935, he moved into the design department at City Machine. He continued with them in the design of dies, fixtures and special machines after graduation from the University of Toledo with his mechanical engineering degree in 1937. In 1942, he started his own company.

Peterson has taught courses in mechanics, mechanism and advanced die design at the University of Toledo. As an ASMer in the Toledo Chapter, he has been on the educational committee, and chairman of the stamping session in the 1954 educational series.

He was one of 15 members of the Pressed Metals Institute-ECA team which studied the productivity of stamping plants in Great Britain in 1951.

Ray Peterson is widely known for his ASTE activities. Chairman of their National Standards Committee in 1952, he served as secretary of ASTE in 1954, and is now treasurer.



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R. E. Peterson

R. E. PETERSON is chairman of the ASM Committee on Stress Concentration. He has been manager of the Mechanics Dept. of Westinghouse Research Laboratories since 1931.

A native of Illinois, he took his B.S. in mechanical engineering at

the University of Illinois in 1925 and an M.S. in theoretical and applied mechanics before joining Westinghouse in 1926.

He is the author of "Stress Concentration Design Factors", and is on the faculty of the Pitt-Westinghouse graduate program.

R. E. Peterson is a past president of the Society for Experimental Stress Analysis. In ASTM he is chairman of Committee E-9 on Fatigue and vice chairman of the Simulated Service Testing Committee. He is a fellow of ASME, chairman of the advisory board of Applied Mechanics Reviews, and a past chairman of the ASME Applied Mechanics Div. He also serves as chairman of ASA Committee Z10.3 on Mechanics Symbols.



William A. Reich

A native of Pittsburgh, Reich graduated from Carnegie Tech in 1938 with a B.S. in metallurgical engineering. He joined the Research Laboratory of G. E. in 1938. A year later, he transferred to the Schenectady Works Laboratory and was head of its metallurgical section from 1945 to 1953. He taught defense courses in metallurgy at Rensselaer Polytech and Union College from 1939 to 1944.

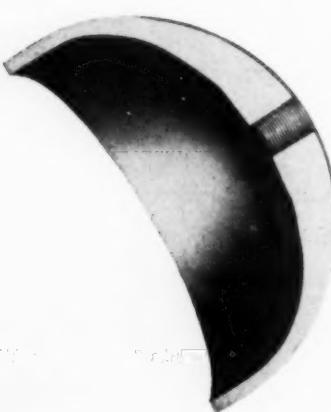
William A. Reich

BILL REICH, chairman of the ASM Committee on Powder Metallurgy, is manager of advance development engineering, Carboloy Dept., General Electric Co.

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Bill Reich has been an ASM member since 1936 and was chairman of the Eastern New York Chapter.

Ralph G. Thompson

RALPH THOMPSON, chairman of the ASM Committee on Copper, is engineering manager, materials and process laboratory, major appliance laboratories, General Electric Co.

Thompson is a graduate of Iowa State Teachers' College and received his M.S. degree from the University of Iowa in 1929. He has been employed by General Electric during all of his active business career. He was located in the Schenectady Works Laboratory from 1929 to 1951, in Louisville since then. Prior to 1949, his chief responsibility was in nonferrous metallurgy; since 1949, his duties have been primarily administrative.

An ASM member since 1944, he is currently a member of the executive committee of the Louisville Chapter. He has been on ASTM Committees B-5, B-6 and B-7.

The Notched Slow-Bend Test*

ONLY by careful study can the ordinary fractologist derive any meat from this somewhat unorthodox though fairly interesting fare on fracture. The difficulties stem both from differences in point of view and from what are apparently language barriers; to wit, the caption for Fig. 5—"Chance to fibrous fracture p up to beyond neutral axis . . .". This latter is also found in references to a "wavelength" of fracture when speaking of fluctuations in ductile-brittle behavior along a bar; to "center of gravity" for centers of statistical plots; to "examinations" of increasing severity when speaking of something quite different from the ordinary meaning of this word; and to an ambiguous "natural fibrous crack" as opposed to a notch.

*Digest of "Brittle Fracture—the Notched Slow-Bend Test as a Criterion", by J. E. de Graaf and J. H. van der Veen, *Iron and Steel*, Vol. 27, Dec. 11, 1953, p. 590-594.

From more technical considerations, the article is difficult to assess in absence of a precise description of the notch angle, width, or shape, though mention, without reference, is made to an earlier paper which apparently carries the test details. Next, the data are largely given in relation to the "neutral axis" of the original stress system, without commenting upon the fact that this shifts immediately upon loading in a bend test such as that upon which the present investigation depends.

Finally, certain minor misunderstandings appear in such statements as this, that the energy absorbed by crystalline fracture is ". . . obviously only caused by the . . . part . . . having shear-fractured edges . . ." It should be noted that there is an important cohesion even across those crystallographic planes which separate by cleavage, of course.

Aside from this lack of mesh with current fractology, the authors present interesting data for 1-in. steel bars using a notched slow-bend test and a pressed notch of standard 3-mm. depth, otherwise varied from 1 to 8 mm. Inspection of the frac-

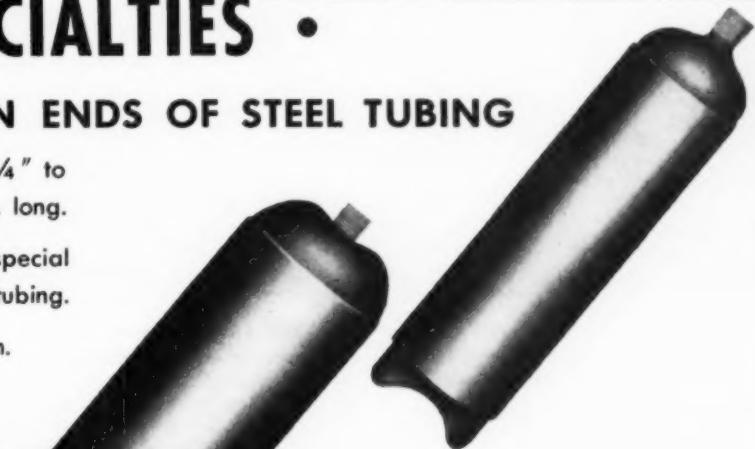
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tured surfaces is made from the standpoint of relating the ductile-brittle transition front to the tip of the notch and to the original neutral axis. Much emphasis is placed upon this neutral axis; and, although that position is very likely significant for more than one reason, the present reviewer feels that the lack of attention to other factors affecting the fracture behavior within the body of the specimen renders a fair proportion of the argument unconvincing.

A maximum tendency for brittle fracture is found in the compression zone, with a minimum at the original neutral axis.

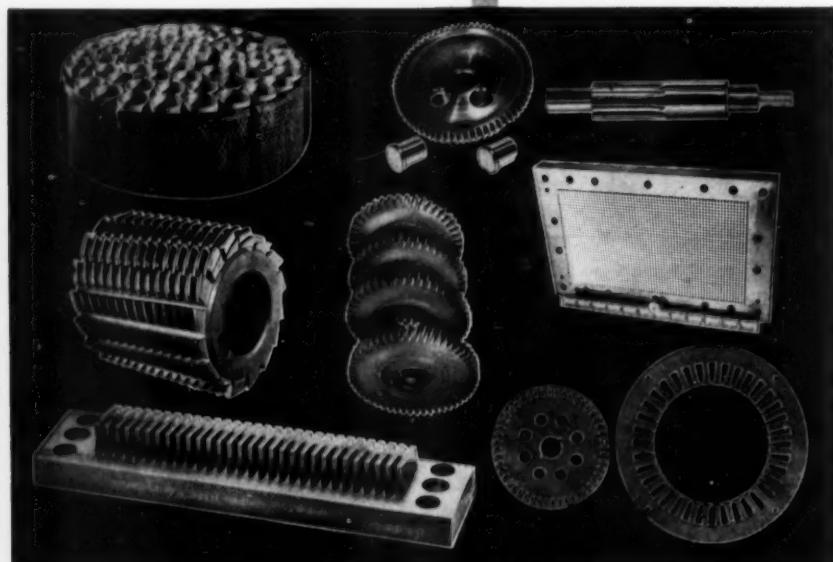
The authors then compare results of Charpy V-notch tests, using statistical analysis to find a "reliability interval" which might aid commercial inspection procedures. A range of $\pm 16^{\circ}$ C. was found for $p=0.95$, this being twice as great as the range for the bend-test data. The authors point out that any mechanical test,

such as the impact test, which reports total energy to fracture largely masks the energy of fracture propagation by the energy required to initiate fracture. They do not believe that these two categories of energy are simply related; therefore a study of fracture appearance is likely to afford a more accurate measurement of transition temperature than the usual mechanical studies. They conclude by recommending the notch-bend test, a rating of transition temperature by visual inspection of the macrofractography, and particularly the use of what they call "mm. fibrous" as a measure of the depth of penetration of the preliminary ductile separation when fracture occurs within the transition range.

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STRESS-CORROSION cracking of steel is often called "caustic embrittlement" because it is frequently caused by strongly alkaline solutions, but the term is considered incorrect by these authors since the action is merely crack formation without any embrittlement of the metal between the cracks. Three conditions must exist to cause this failure, namely: (a) contact with a medium which produces no general corrosion but only a selective attack, (b) tensile stress of sufficient magnitude, and (c) a susceptible steel.

Sodium hydroxide solutions most commonly produce this kind of failure, although alkali nitrates are also responsible. The temperature must generally be above 120° F. for solutions of 50% strength, but weaker solutions can cause cracking at higher temperature. Effective stresses range upward from about half the yield strength, with the rate of failure rising rapidly as the yield strength is exceeded. Common steels vary greatly in susceptibility to stress-corrosion

(Continued on p. A-144)

*Digest of "Stress-Corrosion Cracking of Nonalloyed and Low Alloyed Steels and Its Avoidance by Additions of Titanium or Tantalum-Columbium"; by E. Baerlecken and W. Hirsch, *Stahl und Eisen*, Vol. 73, June 1953, p. 785 to 789.

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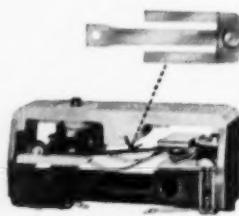
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Stress-Corrosion . . .

(Continued from p. A-140)
cracking; aluminum-killed steels are less susceptible than others, and de-carburized or coarse-grained steel more susceptible, all other things being equal.

The authors tested various steels for susceptibility to stress-corrosion cracking by immersing shackle or stirrup-shaped specimens in boiling calcium-ammonium nitrate solution according to Jones's method (*Engineering*, Vol. 3, 1921, p. 469 to 470). This method apparently was used for all the tests reported in the paper, although another method of stressing rings by driving tapered pins through them is also described.

Of the several means available for preventing stress-corrosion cracking, as by stress-relief heat treatments, stressing the surface in compression, or by cathodic protection, the most practical way is to use a resistant steel. The most resistant steels known were the aluminum-killed, until these authors tested steels having more titanium than is required for deoxidation and denitration.

The titanium steels contained less than 0.1% carbon, 0.5% manganese, 0.3% silicon, and 0.5 to 0.75% titanium. They were tested in three conditions of heat treatment. Each result reported was based on a series of 8 or 10 tests. If no cracks occurred in the Jones test in 21 days, the steel was considered stable. The steels

with Ti:C ratio below 4 cracked in a few days; those with a higher ratio were stable for a heat treatment at 1380° F. After heat treatment at 2190° F. it required a Ti:C ratio of 6.7 for stability of air-cooled specimens, or 8.4 for those that were furnace cooled.

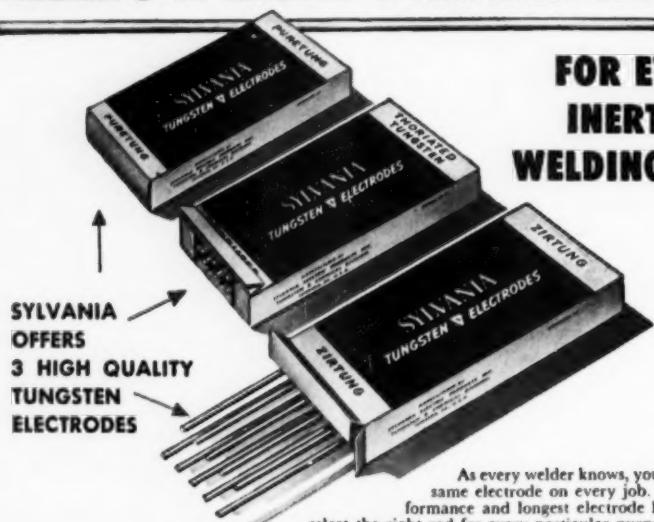
Steels treated with various amounts of a tantalum-columbium ferro-alloy containing twice as much columbium as tantalum, and not with titanium, were also tested in the same way. The steels with Ta-Cb:C ratio below 6 cracked in a few days. Some of the specimens of this group with Ta-Cb:C ratios between 6 and 11.5 were stable after heat treatment at 1380° F. only; but all the specimens with Ta-Cb:C ratio above 11.5 were stable whether heat treated at 1380 or 2190° F.

Specimens of steels treated with aluminum, titanium, and tantalum-columbium were tested in a similar manner after heating for 2 hr. at 2190° F. for grain coarsening, and after decarburizing for 10 hr. at 1830° F. All the aluminum steels heated to 2190° F. failed within 6 days, and only 40% of those heated for decarburizing resisted cracking for 21 days. None of the titanium or tantalum-columbium steels developed cracks in 21 days.

Since the stability of the titanium and tantalum-columbium steels was not impaired by high temperatures, their stability after welding was tested. Arc welds were made with three kinds of rods: austenitic stainless steel stabilized with tantalum-columbium, a steel alloyed with Ta-Cb only (0.065% C, 2.27% Ta + Cb), and a chromium-molybdenum steel (0.12% C, 1.32% Cr, 0.46% Mo). Each of these rods was used to make a series of welds on each of the three steels, aluminum-killed, (0.27% C, 0.08% Al), titanium (0.07% C, 0.58% Ti), and tantalum-columbium (0.08% C, 0.92% Ta + Cb). The welded specimens were tested for resistance to stress-corrosion cracking as described above, both in the as-welded condition and after they had been air cooled from 1380° F.

None of the six series of welds on the aluminum steel was completely stable, the best record being 70% stable for the as-welded series with the 2.27% Ta + Cb rod. A migration of carbon was detected from this 0.27% C steel into the weld deposit
(Continued on p. A-146)

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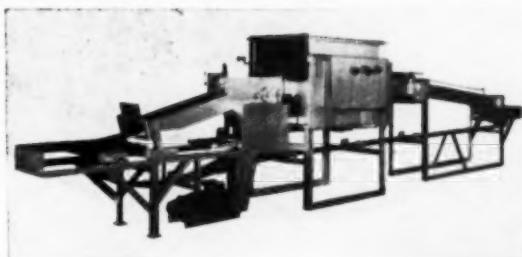
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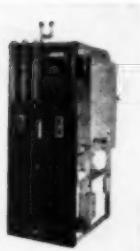
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Stress-Corrosion . . .

(Continued from p. A-144)

at the boundary after heat treatment, and since the stress-corrosion cracks occurred at this boundary in the heat treated specimens instead of in the heat-affected zone as in the as-welded specimens, the larger percentage of failures in the heat treated series was ascribed to the decarburized boundary. The same result and structure were observed in welds made with the austenitic rod, but not in those made with the chromium-molybdenum steel rod.

Weld series showing 100% stability for 21 days were obtained with the austenitic electrodes on both the tita-

nium and the tantalum-columbium steels, whereas the best record with the chromium-molybdenum rods on both steels was 70% stability for the series. With the Ta-Cb electrodes only the heat treated series of welds was 100% stable on both steels. None of the stress-corrosion cracks in any of these failed welds occurred in the weld deposits.

Gas welds using a neutral flame were made with the same steels, welding rods and heat treatment, and tested in the same way. Again no complete series of stable welds was obtained on the aluminum steel, but on the titanium steel only the heat treated series made with the austenitic rod was 100% stable. The poorer showing of this steel in gas

welding is ascribed to oxidation of titanium at the weld boundary, or carburizing by the flame. The tantalum-columbium steel gave approximately similar results from the gas welds as from the arc welds.

The authors conclude from these results that welds that are not susceptible to stress-corrosion cracking can be made with austenitic welding rods on steels in which the carbon is adequately stabilized by titanium or tantalum and columbium. However, since their tests were of only 21 days duration, and they used only one corroding medium, it would seem safer to conclude merely that such steels are definitely superior to the best previous low-alloy steels in resistance to this type of failure.

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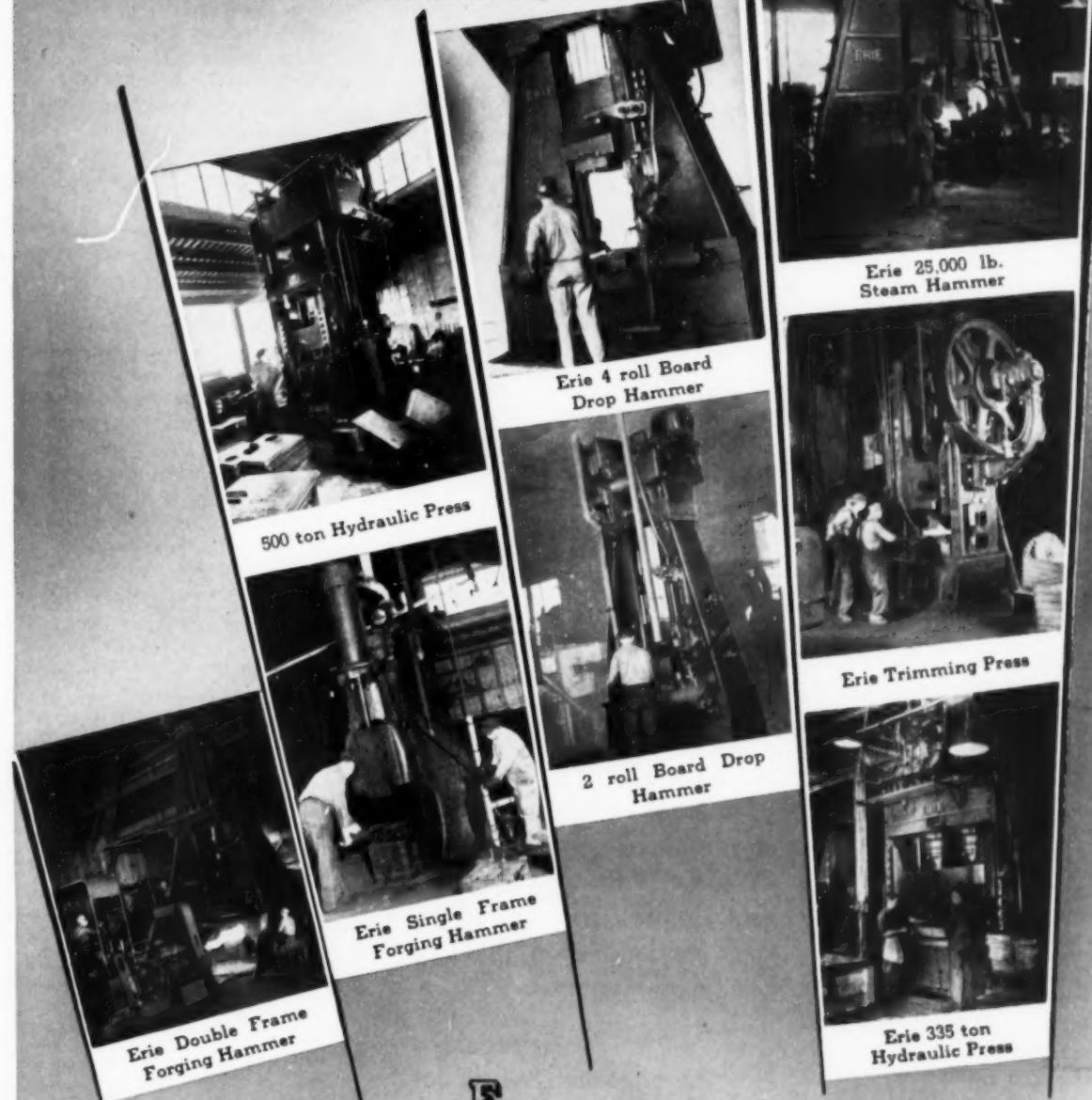
THIN-WALL steel tubing produced by roll forming strip stock and resistance welding the seam is widely used throughout the metal fabricating industry and efforts are constantly being directed toward lowering its cost by increasing the speed of rolling and welding, improving the design of forming rolls and other equipment modifications.

Crux of the problem appears to be in the welder, usually comprising a rotating transformer, the secondary of which terminates in two wheel-shaped electrodes contacting the tube. An air gap of from 0.050 to 0.125 in., varying according to the wall thickness of the tubing, separates the electrodes and bisects an annular groove, called the electrode radius, extending around their circumference. A weld support or back-up roll positions the tube into contact with the rotating electrodes, the seam being centered in the air gap. Frequency of welding voltage is generally 180 cycles per sec. (cps.), this being derived from a motor-driven alternator. Welding current is regulated by varying the excitation of the alternator.

(Continued on p. A-148)

* Digest of "Studies in Resistance Welding Yield Improvements in the Manufacture of Thin-Wall Steel Tubing", by Donald P. Worden, *General Motors Engineering Journal*, Vol. 1, March-April 1954, p. 14-18. Published by General Motors Corp.

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Welded Tubing . . .

(Continued from p. A-146)

Tests have shown that with a frequency of 180 cps. and a tube wall thickness of 0.026 in., maximum speed of travel is about 88 ft. per min., power input being 280 w. per ft. per min. Increasing the speed causes minute cyclic discontinuities or voids in the weld, referred to as "stitching". Distance between these voids increases with speed, at 100 ft. per min. being 0.055 in. Higher power input has no appreciable effect on spacing of the voids.

By coordinating frequency and speed factors, it is found that at 88 ft. per min. and with 180 cps. current, each point on the seam travels 0.048 in. in 1/360 sec., or the time of a half-cycle, recognizing that power varies from zero to twice the effective or root mean square value in each half-cycle. Since 0.048 in. is the unit welding distance, any increment of the seam is subjected only once to all instantaneous welding voltages comprising a half-cycle.

Since a void or nonweld is caused by the coincidence of zero current and the completion of movement through the unit welding distance,

it becomes necessary to preclude the possibility of such coincidence if voids are to be eliminated. This can be done by using direct current, which makes equipment too complicated and costly, or by increasing the current frequency. By the latter method, stitching is not encountered with a doubled frequency until speed has been doubled.

Selection of a 960-cps. frequency seemed to offer the possibility of a five-fold increase in speed, so experiments were conducted with a 400-v., 25-kva., 120-turn transformer. Because of high leakage reactance, figured at 58%, the primary voltage had to be increased to 700 v. in order to make the weld.

Leakage reactance is described as the magnetic flux in any transformer which does not link both the primary and secondary windings. Its effect is to require more primary voltage to produce desired secondary voltage.

The first experimental transformer was constructed with mechanical parts from an old 180-cps. unit. Later another transformer was designed for lower leakage reactance. It was a 50-kva., 85-turn, 400-v. unit with calculated leakage reactance of 17%, later checked out by short-circuit test at 23%. Special attention was devoted to the core, final choice being 5-mil grain-oriented steel with a calculated flux density of 30 kilo-lines per sq. in.

The new transformer showed no weld stitching at tubing speeds of 400 ft. per min. and power requirement was only 125 w. per ft. per min. A reduced bead size was noted, some samples being welded without any flash removal being necessary as in conventional practice. Wall thickness greater than 0.035 in. presented some problems, but increasing the electrode air gap helped.

Studies showed that 14 kw. is required to weld at 50 ft. per min., while 50 kw. is required at 400 ft. per min. This is equivalent to 280 and 125 w. per ft. per min., respectively, a decided gain in efficiency resulting from the higher speed. Power for welding increases about one-half as fast as tubing speed.

The foregoing experimental work was the basis for design of a new group of welders and thin-wall tube mills, now in operation at the Rochester Products Div. of General Motors Corp. Because the 960-cps.

(Continued on p. A-150)

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Welded Tubing . . .

(Continued from p. A-148)

transformer is not so well suited to tubing with wall heavier than 0.035 in., a 420-cps. transformer was decided upon, permitting processing of tubing up to 0.070 in. wall.

Strip steel stock for welded tubing has an important bearing on resultant product quality. A fully aluminum-killed steel is the most

satisfactory. Another factor influencing weld quality is edge conditioning of the strip prior to forming. Extremely sharp paring-type tools give the best tubing, in some instances permitting a reduction of welding temperatures without adversely affecting the weld. The explanation appears to lie in the pattern of exposed edge grains. If they are smooth and are not deformed, the edges are more amenable to welding.

A. H. ALLEN

Causes of Filiform Corrosion*

FILIFORM corrosion is a thread-like rusting which occurs on some metals under a protective coating. These threads are usually in the form of a haphazard pattern of shallow channels in the metal. The conditions under which filiform corrosion occurs are: (a) an atmosphere of high relative humidity capable of producing corrosion on the bare metal; (b) a semipermeable coating on the metal having sufficient elasticity to yield without rupture when the corrosion products from filiform attack are produced under it; (c) oxidation of the metal first to an unstable state and then to a stable form.

Filiform corrosion has been observed on surfaces of ferrous alloys, aluminum and magnesium. In the corrosion of iron and steel, the corrosion product in the active head of each thread is blue in color, indicating the unstable ferrous state. As the thread grows the product changes to the stable ferric state which is red. Magnesium corrodes first to the unstable black amorphous hydroxide in the active head and leaves a stable white crystalline form of corrosion product in the body of each thread. Aluminum can form oxides in different states and degrees of hydration and therefore fulfills one of the basic requirements for filiform growth.

Filiform may originate from a scratch, edge, speck, piece of dust or lint or any imperfection or discontinuity in the protective coating. These coatings include such things as tin plate, silver plate, gold plate, certain phosphates and vehicle types such as drying oils, oleo-resinous binders, pure and modified phenolic varnishes, alkyls, lacquers, vinyl copolymers and amine-modified ether resins and ether esters, to mention a few. Covers for jelly cans, tools coated with an oil film, refrigerator doors, coated metal tile and chromium-plated automobile hardware are some examples where filiform corrosion has been observed. Industrial finishers are especially concerned with this type of attack.

(Continued on p. A-152)

*Digest of "Filiform Corrosion", by M. Van Loo, D. D. Laiderman and R. R. Bruhn, *Corrosion*, Vol. 9, August 1953, p. 277-283.

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METAL PROGRESS; PAGE A-150

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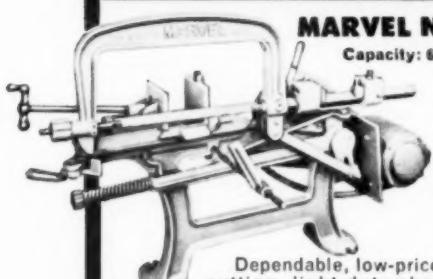
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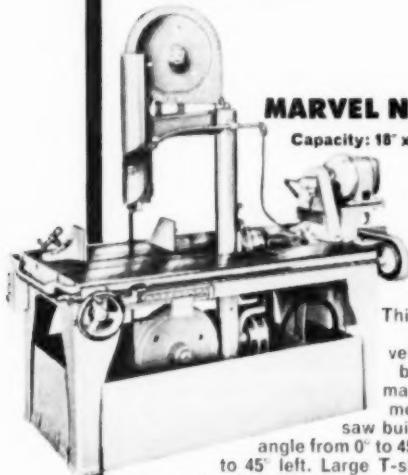
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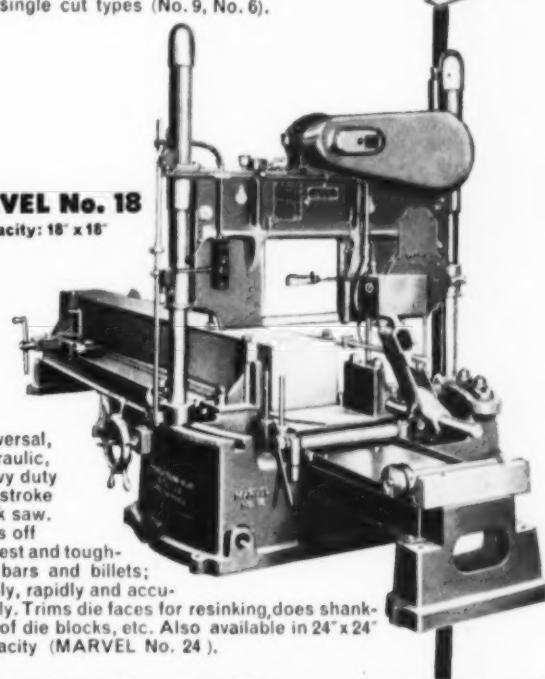
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Filiforms . . .

(Continued from p. A-150)

The definite connection between relatively high humidity and filiform growth is known from early investigations. This work shows that cold rolled steel panels coated with baked enamel and treated to initiate rusting by breaking the coating and exposing the sample over an acetic acid solution were susceptible to filiform growth only when tested in

atmospheres of over 65% relative humidity. The tests were conducted over solutions of sulphuric acid or sodium hydroxide in which the relative humidity was controlled from slightly above 5 to 100% at 75° F. Corrosion was more pronounced in the atmosphere over sulphuric acid, but no filiform was observed below 65% relative humidity with either of the solutions. The growth was quite active between 80 and 90%, the threads became wide above 90% and

blisters appeared at about 95% relative humidity.

It is of interest to note that no connection has been found between biological activity or the metallography of the metal surface and filiform growth.

The filiform process involves three steps: the initiating mechanism, the driving mechanism, and the directional mechanism. Filiforms are initiated by tiny anodes controlled by adjacent small cathodes. The permeability of the protective film controls the rate at which the corrosive atmosphere reaches the film-metal-air junction and thus controls the corrosion process within the active head of the filiform. Electrochemical action in the form of an oxygen-concentration cell set up by the difference in concentration of oxygen between the active head and the inactive body of the filiform is the driving mechanism. The oxygen concentration is in turn controlled by the corrosion within the active head.

As the corrosion product from the advancing filiform lifts the coating, there is a temporary localized low concentration of oxygen which subsequently rises as the permeability of oxygen proceeds into the region. Oxygen is consumed in the active head by depolarization and oxidation reactions. The formation of the stable corrosion product controls radial growth of filiform. Under ideal conditions of temperature, humidity, film thickness and metal surface, filiform will grow in a straight line.

The directional mechanism is the conversion of the corrosion product to the stable state which prevents radial growth and imparts linearity. When filiforms meet they can change direction, die out or blend into one filiform depending on the angle at which one thread strikes another or if two active heads meet as in the latter condition.

There is no cure-all for filiform corrosion. Inhibitive pigments in metal primers permit filiform corrosion under suitable conditions but usually in a retarded form. Filiform corrosion will cease if the humidity of the atmosphere is controlled to a point below which rusting does not occur. Avoiding imperfections in the coating and the use of coatings with sufficient inelastic properties to cause rupture by corrosion products reduce filiform corrosion.

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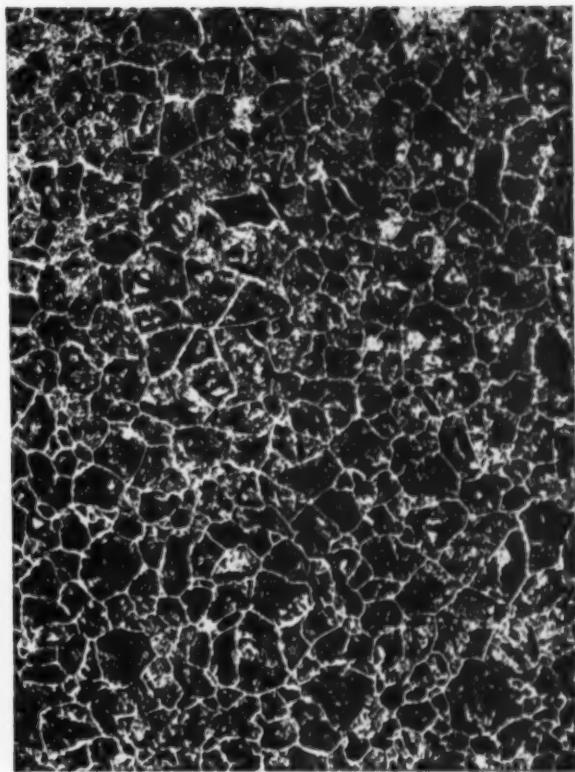
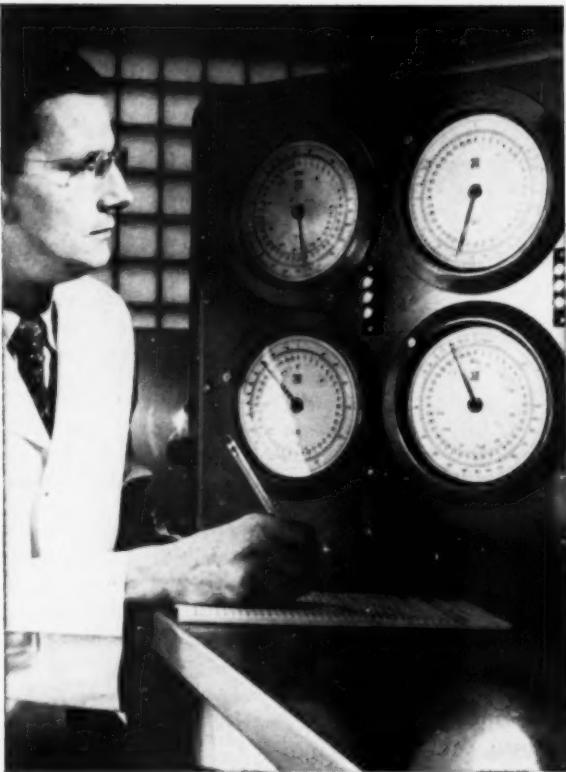
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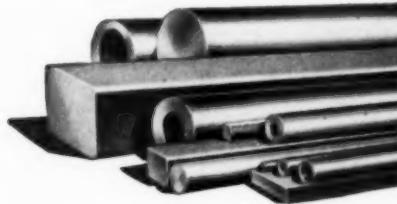
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X-Ray Measurements of Lattice Distortions in Martensite*

THE LARGE change in the lattice constants of martensite caused by increasing the amount of carbon dissolved in it suggested that there might be appreciable variation in the spacing of the iron atoms. Carbon steels containing less than 0.5% carbon were chosen for study because the change of the ratio of the intensities of the (110) and (220) lines is not complicated by the resolution of the doublet of the tetragonal lattice and by the presence of austenite. Partial decomposition of the martensite in these steels occurs during quenching and prevents an exact dependence of distortion on the amount of carbon in solution. The absence of resolution of the doublet of the tetragonal lattice can perhaps give only a nominal value of the mean-square diffraction. However, such measurements can give a general idea of the magnitude of distortion and of the change of binding in the lattice of a supersaturated solid solution of carbon in alpha iron (martensite).

To determine the character of the distortion of the crystal lattice of martensite, X-ray intensity measurements were made on quenched steels containing 0.35 and 0.41% carbon at 73 and -301° F. Specimens were 0.9 mm. in diameter, and filtered cobalt radiation was used. It was found that the ratio of the intensities of the (110) and (220) reflections was 5% lower at -301° F. for pure alpha iron, 10% for 0.35% carbon steel, and 11.5% lower for 0.41% carbon steel. That is, the change in the thermal factor is greater for the solid solutions than for pure iron. The characteristic temperature of the martensite was calculated to be 680° F. for the 0.41% carbon steel and 698° F. for the 0.35% carbon steel. These lower values, compared to those for alpha iron, are attributed to a weakening of the binding of the atoms in the lattice and to an

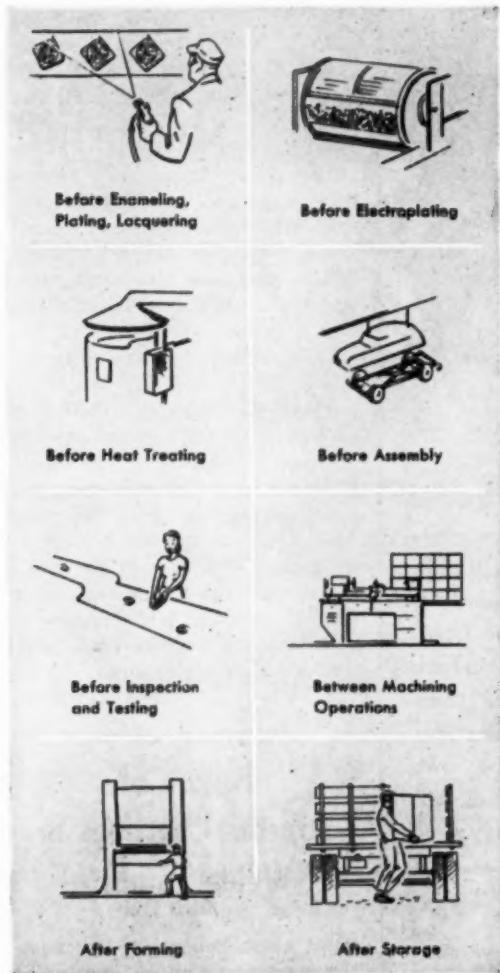
(Continued on p. A-156)

*Digest of "Causes of the Weakening of the Intensity of X-Ray Interference of Martensite", by V. A. Il'ina, V. K. Kritskaya and G. V. Kurdyumov, *Doklady Akademii Nauk SSSR*, Vol. 85, 1952, p. 773-75.

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Lattice Distortions . . .

(Continued from p. A-154)
increase in the amplitude of thermal vibrations.

The higher value of the ratio of reflections for the 0.41% carbon steel at -301° F. than for alpha iron indicates the presence of significant static distortions of the martensite lattice. A calculation gave a mean-square displacement of the iron atoms from the lattice points of 0.09 Å in a direction normal to the (011) plane. These static distortions accounted for slightly more than half of the difference between the ratio of reflections for the 0.41% carbon steel and the alpha iron, and the remaining difference was caused by changes in dynamic distortions; that is, by changes in the strength of binding.

Thus, the martensite lattice is characterized by the presence of significant deviation of the center of vibration of the atoms from the lattice points. Moreover, the presence of carbon in solution leads to a significant increase in the mean deviation of the iron atoms during thermal vibrations and therefore to a weakening of the interatomic binding compared to alpha iron.

A. G. GUY

Failure of Structural Sections in Welded Ships*

THIS PAPER summarizes the information accumulated during the past ten years on the fracture of welded ships and gives complete details of the investigations which were made of the structural steel sections involved in the failures.

Of the 5000 merchant ships built during World War II, more than 20% of these developed cracks in varying degrees up to April 1946, when most of the ships were less than three years old. From November 1942 to December 1952, more than 200 ships sustained serious fractures and at least 13 ships broke

*Digest of "Investigation of Structural Failures of Welded Ships", by M. L. Williams and G. A. Ellinger, *Welding Research Supplement*, Vol. 28, October 1953, p. 498S-527S.



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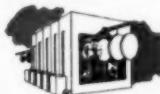
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Welded Ships . . .

(Continued from p. A-156) completely in two and 25 other vessels had complete fractures of the strength deck or the bottom. Although fractures have occurred in riveted ships, these failures usually ended at discontinuities at the riveted joints and did not spread to adjoining plates. Since a welded structure is continuous, cracks may propagate across welds into adjacent plates and thus cause a complete structural failure of the assembly.

Samples from 100 ships in which fractures occurred were examined prior to December 1952. Preliminary studies included (a) determination of the location of the samples with respect to the fracture and the ship structure, (b) visual examination of the fractures and welds, (c) determination of the starting point of fracture from this examination or from available reports, (d) evaluation of factors — such as loading and temperature — which may have contributed to the origin and propagation of the fractures. Laboratory investigation of the plates included de-

tailed macro and microscopic examination of fractures and welds, tensile tests, Charpy V-notch impact tests over a range of temperatures, chemical analysis of the plates for 14 elements, vacuum-fusion analysis for oxygen, hydrogen and nitrogen. Measurements of the reduction in thickness at the fracture edge were made wherever possible and microscopic examinations were made of all of the plates in which fractures originated.

The temperature at which fracture occurred was recorded as water temperature for plates fracturing below the water line or as air temperature for plates fracturing above the water line. Fractured plates were further classified into source plates that contained the origin of fracture, through plates in which the crack passed and contained neither the source nor the end of fracture, and end plates in which the crack terminated. Fractures always originated in some kind of a notch or discontinuity, either mechanical or metallurgical.

Notch-bar test specimens were standard Charpy V-notch (shown in "A.S.T.M. Standards", 1952, Tentative Standard E23-47T). The transition temperature is taken as that point at which the Charpy test value falls below 15 ft-lb. energy absorption.

Detailed descriptions are reported of the fractures in the 100 plates with respect to origin of crack, thickness of plate at fracture and 1 in. away, and structural defects such as notches and poor welds. Over half of the fractures started in the vicinity of structural features — such as hatch corners, ladder cut-outs or other openings — or at the abrupt end of stiffeners, such as bilge keel, longitudinal and doubler plates or other discontinuities which act as stress-raising. Over a third of the cracks started in defective welds, some related to structural notches, and others in which the only notch present was that resulting from welding defects. A common origin of cracks was at the arc strikes or craters caused by welders striking an arc on the plate outside of the weld zone.

Several distinctive features of the cracks were common to all of the fractures. All were of the brittle type, the break being perpendicular to the plate surface with very small reduction in plate thickness (usually less

(Continued on p. A-160)



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Welded Ships . . .

(Continued from p. A-158)

than 3%) at the edge. Evidence of strain or plastic deformation was lacking, as shown by absence of cracks in the scale or paint near the fracture. The stress in the plate must have been less than the yield point a very small distance from the edge of the crack.

The fractures are characterized by a pattern in the broken surface, the pattern being described as chevrons, herringbones, or arrowheads. These arrowheads point to the origin of fracture; the authors show this feature in a number of illustrations.

The amount of reduction in plate thickness at the edge of the fracture was generally very slight but a few breaks showed a thin lip of a partial shear fracture instead of a complete cleavage break. This decrease in the thickness at the fracture edge varied from 0.4 to 4.0% for the plates with a brittle fracture. Thickness reductions of about 30% were found in two small areas which showed a double-shear fracture.

The laboratory study of some 100 cracked ship plates included a complete metallographic survey, conventional tensile and bend tests as required in the specifications, and a complete series of Charpy V-notch impact tests on each plate at temperatures from 0 to 150° F.

The microstructures were typical of hot rolled carbon steels. Some plates had a large number of inclusions, some were excessively banded, some indicated rimming steels, but most of the samples indicated semikilled steels. In the vicinity of the brittle fractures, deformation of the grains was mostly confined to the grains in which fracture occurred, while in some of the shear (ductile) breaks the deformation appeared at some distance on each side of the break and also ahead of the fracture. This indicated a highly localized deformation in the brittle fractures as compared to the much larger volume of metal that was deformed in ductile fractures.

Two unusual features were observed in many of the samples. These were Neumann bands, which were common in the grains along the brittle fracture, and directional

(Continued on p. A-162)

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Welded Ships . . .

(Continued from p. A-160)
cracks. These were not found in plates having a ductile break. The directional cracks found near the brittle fractures were entirely trans-crystalline and were marked by displacement or offset of the grain material along one side of the crack. Occasionally the cracks were so numerous as to indicate a zone of shatter such as appears in glass

fractures. The distinct difference between the shock and shatter cracks associated with the brittle fractures as compared to the cold worked deformation structure of the ductile breaks is very evident in the micrographs reproduced in the article.

The grain size of the plates was determined by comparing the fracture surface of broken impact tests made at a temperature *below* the transition temperature where a brittle cleavage fracture was obtained. Visual observation of these

enabled the determination of fracture grain size within an accuracy of one A.S.T.M. grain size in the range of No. 2 to No. 7. The grain sizes so determined were generally proportional to the thickness of the plates in the range of 0.52 to 1.25 in. thick. No tabulation of grain sizes is given in the paper, nor were Charpy tests or transition temperature correlated with grain size.

The mechanical properties of the plates were studied by means of transverse and longitudinal tensile tests and notched-bar tests with both longitudinal and transverse orientation, together with notches cut parallel or perpendicular to the plate surface. The tensile tests gave conventional strength values; thus all samples met specification requirements. The impact tests gave a wide scatter of results for test conditions, involving temperature of test, orientation of sample, notch direction and grain size, and the only condition which gave some uniformity and reproducibility was for samples cut in the direction of rolling and having the notch perpendicular to the plate surface. Specimens made this way were used in the determinations for the transition temperature of each plate steel, the chemical composition on the transition temperature and for the statistical summaries of the effect of plate thickness (grain size).

To establish the relationship of Charpy V-notch with the transition temperature for each plate, four specimens were broken at each temperature and average values were plotted; these four specimens were cut from different places in the plate to avoid local variations. The impact values at the various test temperatures are plotted, using a value of 15 ft-lb. as the minimum measure of ductility with the temperature corresponding to this value being the transition temperature for that particular plate.

An extensive statistical survey of all of the impact test data is included. The plates in which cracks started had the highest average transition temperature (about 80° F.) with none below 55° F.; some of these plates had transition temperatures as high as 150° F. Plates which contained a brittle fracture through the plate showed an average of 65° F., with some as low as 20° F.; plates in which the cracks

(Continued on p. A-164)

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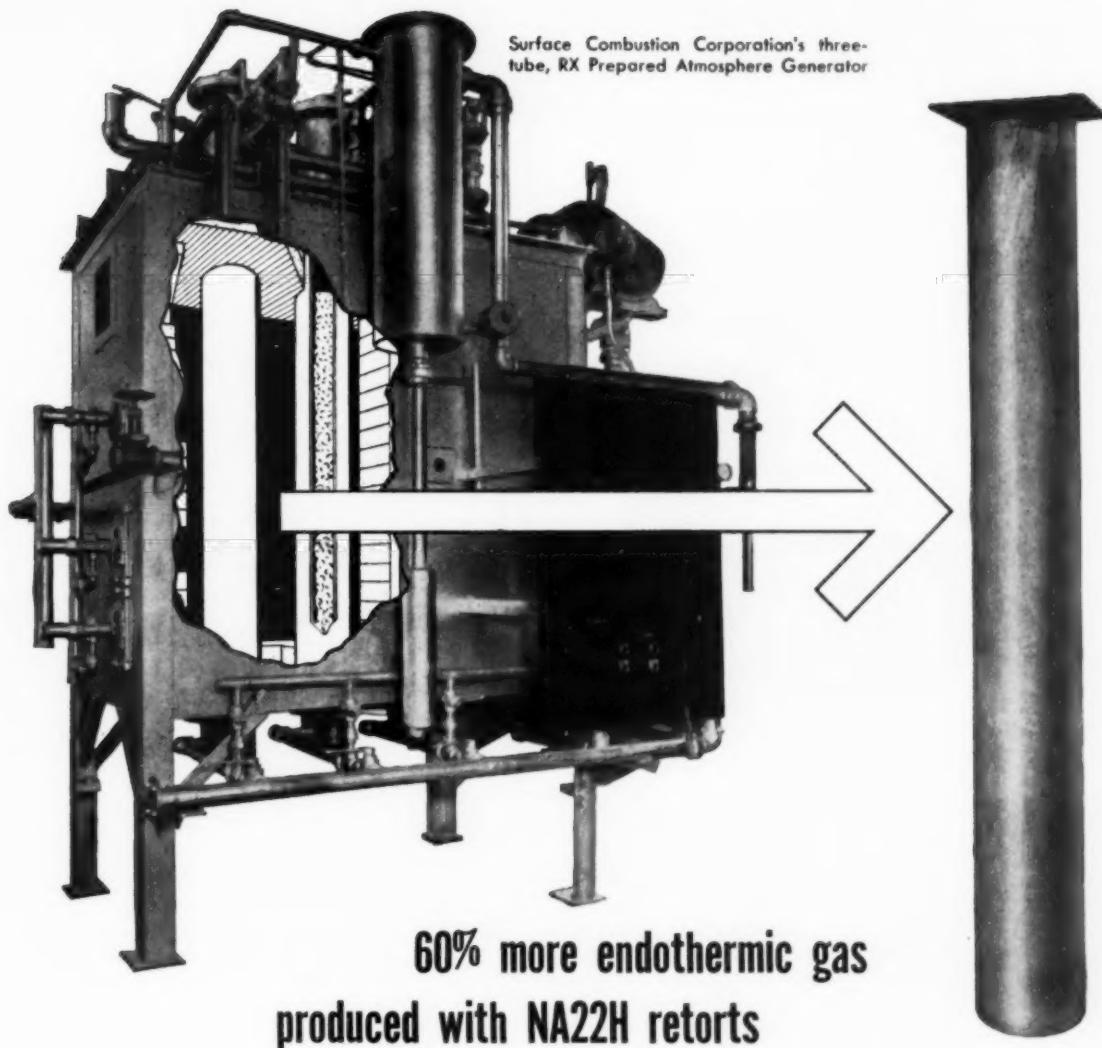
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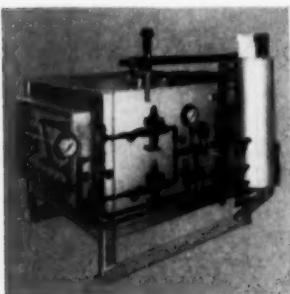
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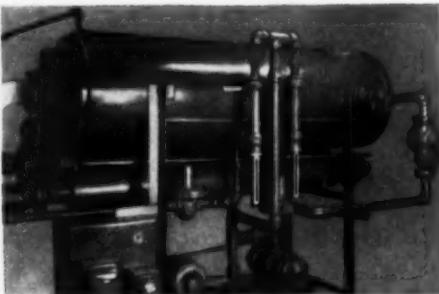
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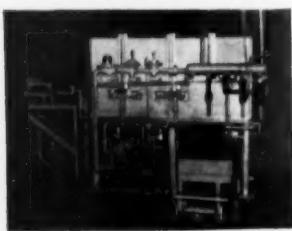
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Welded Ships . . .

(Continued from p. A-162)
stopped and had some ductility had an average transition temperature of 49° F. and a minimum of 0° F.

The service temperatures observed at the time the cracks started on ships ranged from 20 to 78° F. Little relation was found for number of failures and plate thickness; there were 38 fractured plates in the ranges 0.44 to 0.69 in., 37 plates in the range 0.70 to 0.80 in., and 32 plates in the range 0.81 to 1.25 in.

Multiple correlation plots of the 15-ft-lb. transition temperature versus carbon content, manganese, phosphorus, silicon, and sulphur are contained in the paper. The effect of increased carbon content on raising transition temperature is quite significant, but the effect of the other elements seems to be quite vague. This is attributed to the small range of variation of the elements (0.01 to 0.04% P, 0.01 to 0.12% Si). The authors concluded from these statistical results that carbon and phosphorus are detrimental because they raise transition temperatures, whereas an increase in manganese or silicon contents is beneficial in lower transition temperature. No influence on transition temperature could be found with respect to hydrogen, oxygen or nitrogen content of the steels.

The results of this investigation indicate that the structural failures in welded ships were caused by stress concentrations and by steel that was notch sensitive at operating temperatures. This conclusion is confirmed by results of laboratory tests of fractured plates, as well as by critical observations of the starting points and the circumstances of the failures.

The starting points of the fractures could be traced, invariably, to a point of stress concentration at a notch resulting from structural or design details, welding defects, metallurgical imperfections or accidental damage. The failures were relatively more numerous at lower operating temperatures, and the few failures that did occur at temperatures higher than about 50° F. were not as extensive or serious as many of the failures which occurred at lower temperatures. The fractures in

(Continued on p. A-166)

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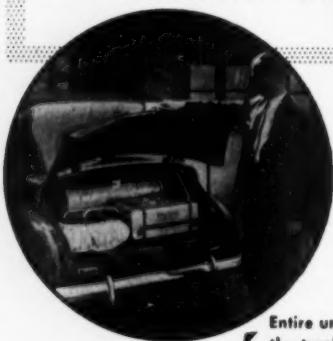
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Welded Ships . . .

(Continued from p. A-164)

the ships were of the brittle type, having very little ductility; however, in tension tests the steels from the fractured plates showed normal strength and ductility, which would meet the specifications under which these steels were purchased.

Relationships between the transition temperatures (determined by Charpy V-notch tests) and the chemical compositions and grain sizes of the steels indicate that notch sensitivity increases as carbon or phosphorus is increased, is decreased by increasing amounts of silicon or manganese, or by decreasing the grain size, and that these effects are apparently additive. The improvement of notch toughness that has been attributed to a higher manganese-to-carbon ratio is more probably a result of the additive effects of increased manganese and decreased carbon content.

E. C. WRIGHT

Mathematics in Quality Control*

QUALITY CONTROL in the large manufacturing industries is actually "statistical" quality control, the adjective having been dropped partly because the word has a considerable degree of mystery for many persons. Quality control may be defined briefly and simply as the science of preventing defects and maintaining the uniformity of a product through the use of statistical methods. In addition to its basic preventive function, this control has the correlated functions of acceptance, or inspection at both receiving and shipping ends, and assurance. The latter calls for extension of quality control into the realm of sales and management.

Probably the most useful tool of the quality engineer is the "average and range" (A and R) chart, devised by Walter A. Shewhart and based on the statistical law that no two

(Continued on p. A-168)

* Digest of "Mathematics Necessary for Quality Control in Mass Production", by Mario Parran, General Motors Engineering Journal, Vol. 1, No. 3, November-December 1953, p. 22 to 27.

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Quality Control . . .

(Continued from p. A-166)

manufactured products are alike but vary according to a definite pattern. The Shewhart chart builds frequency distribution on a time trend basis, with the ordinate being the variable under measurement and the abscissa being time. Its three principal uses are: (a) to determine when to search for assignable causes of variation and take corrective action; (b) as a basis to change production procedures, and (c) to determine machine or process capability.

Three levels of mathematics or mathematical principles are required in the quality control function: simple arithmetic on the inspection line; high school mathematics for technicians, including advanced algebra, plane and solid geometry, trigonometry and, preferably, an elementary course in quality control; and college mathematics for supervisors, covering descriptive geometry, differential and integral calculus, and statistics.

Most of the necessary mathematical work falls on the technician who must handle calculation of control limits, analyze control charts, select sampling plans, study processes by the analysis of variance, make significance tests and finally correlate the whole business.

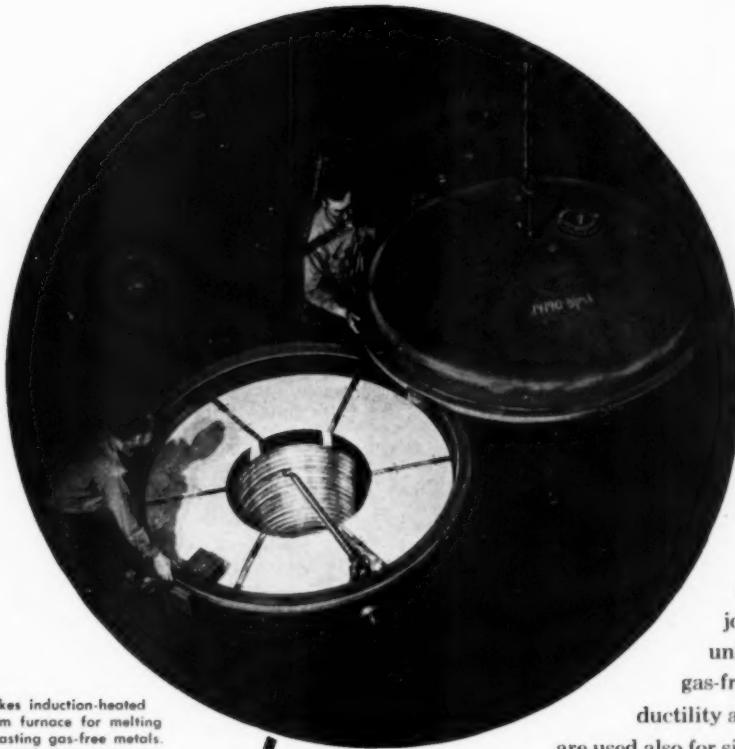
Fortunately, a good bit of the mathematics has been reduced to relatively simple formulas, constants and tables. In sampling, for example, the technician generally will use the Dodge-Romig single and double sample plans, or one of the various plans specified by the armed forces. It was in connection with production for the military during the last war, incidentally, that statistical quality control found wide use.

Some large companies use work sheets for each control problem that explain every procedure for obtaining the actual values to be entered and the arithmetical operations to be performed. This method of solving routine problems is used almost universally in quality control, engineering and design. Although it does not lead to the development of mathematical skill, it has the advantage of making it possible for almost anyone to fill out the work sheets and perform the elementary arithmetic.

(Continued on p. A-170)

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Quantities?



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Quality Control . . .

(Continued from p. A-168)

The work of a quality control technician or supervisor, in addition to solving routine problems, requires that he be able to think mathematically. Often the successful interpretation of data and the solution of problems call for the technician or supervisor to devise new methods of analysis. This cannot be done effectively unless he has a fairly complete mathematical background.

Since statistical principles are used to control dimensions in manufacturing, it is logical that they might be also applied to setting of tolerances in design. Thus, in a machine having three parts bolted together, with specified tolerances in each, the usual way of determining the resultant variation in the over-all length of the assembly would be to add the tolerances algebraically. However, this would hold true only if every piece were made to the maximum tolerance — almost never the case. If the manufacturing process is statistically controlled, the lengths will be normally distributed with most of the pieces being at the mean of tolerance. Under these conditions, 99.7% of the assemblies will be within tolerance.

A. H. ALLEN

Quality of Extrusions*

IN THE extrusion of solid products in copper and aluminum alloys on horizontal presses by the direct process, the greatest safeguards of quality are constant vigilance and attention to apparently insignificant details.

With the semicontinuous casting process used universally for aluminum alloys, surface exudations should be removed by machining; however, not all alloys and sizes of billets need to be machined prior to extruding. Microscopic examinations and ultrasonic scanning are employed to help in selecting aluminum alloy billets of fine grain size and satisfactory freedom from stress cracking.

With certain materials, such as (Continued on p. A-173)

* Digest of "Some Factors Affecting the Quality of Extrusions", by Christopher Smith and N. Swindells, *Journal of the Institute of Metals*, March 1954, Vol. 82, p. 323 to 333.

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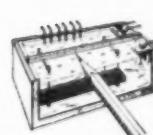
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One pass through the sodium hydride bath will do the job completely. You can maintain uniform speed in production-line descaling. Quick completion of orders means you can substantially cut down on inventory in process.



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No scale-breaking or special racking procedures are required. Finished stock of any size or shape can be completely descaled with the versatile Du Pont process. Even dissimilar metals can be treated in the same bath—at the same time!



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Any pickler can be trained in a few hours to run the Du Pont Sodium Hydride Descale Process effectively. You can do more work with fewer men and less equipment. And you save on time, space and labor costs.



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MD also manufactures Aluminum Pastes and Powders and Gold Bronze Powders for a wide range of uses such as product finishing both metal and plastics, metallic inks, etc. The decoration of many parts can be greatly enhanced with the use of such Metal Pigments. Aluminum pigmented paints are recognized for their outstanding protective qualities and can be used for priming as well as finish coats.

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Numerous Technical Bulletins are available on request.

Extrusions . . .

(Continued from p. A-170)

tough-pitch copper, oxidation of the billet surface during preheating can have a profound influence on the manner in which the metal flows during extrusion and can cause subsurface defects which increase the amount of scrap. Thus, furnace atmospheres or protective coatings, such as whiting or other adherent, inert substances are important in the prevention of surface scaling.

With aluminum alloys it is inadvisable to "force" the heating of billets, for irreparable harm may be done to some alloys. In spite of this, the suggestion that preheating in low-frequency induction units may result in greater economy has certainly attracted considerable attention. It should be pointed out that certain of the strong heat treatable alloys require prior homogenization if very rapid heating is to be used.

The alignment of the press is important, since many extrusion defects can arise from the maladjustment of the pressing stem. With brass, loads of 167,000 psi. appear to be as high as is practicable for a reasonable tool life with normal ratios of billet length to diameter. Low unit pressures require undesirably high temperature for extrusion, which decreases quality and increases scrap resulting from failure to extrude complete billets.

Tool materials must withstand particularly severe conditions of temperature, stress and thermal shock. Dimensional accuracy is one of the main aspects of quality, and it depends on the ability of the dies to maintain their shape without "washing in" or cracking. Variations in the length of die bearing and adjustments of the lead-in taper are used to control the flow through different parts of die openings that are nonuniform in cross section. Other methods of controlling flow are by positioning the part of the section where resistance to flow is high in the middle of the die and by encouraging flow by local application of lubricants to the die.

With copper alloys the higher extrusion speeds produce greater uniformity from end to end of an extrusion with respect to properties and dimensions. This is illustrated

(Continued on p. A-174)

If it's a metal cleaning job . . .

there's an OAKITE cleaner for it

More than 100 efficient Oakite materials and modern Oakite cleaning methods are ready to help you handle any job of getting metals clean. Whatever the soil to be removed; the metal; the equipment used; and the finishing process, you'll find an Oakite Material that can most suitably meet your requirements.

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Extrusions . . .

by the effect obtained by two extremes in extrusion speed on the diameter of material produced from a single-hole die from billets 8 in. in diameter and 26 in. long of a leaded 58% copper, free-machining brass at 1380° F.

	EXTRUSION TIME, SEC.	ROD DIAMETER, IN.	FRONT	MIDDLE	BACK
57	1.558	1.560	1.570		
8	1.559	1.560	1.562		

Many factors influence the maximum speed, which with $\alpha + \beta$ brasses is a complex function of composition, temperature and size of rod. If the speed or temperature is too high, there is a tendency for the brass to build up around the exit side of the die and for the rod to emerge with a grooved surface and below the expected diameter.

Extrusions with excellent surfaces may be produced at speeds up to 100 ft. per min. in alloys of the magnesium silicide type, and to a smaller extent in the aluminum-magnesium alloys; with ultra-strong alloys, speeds may have to be as low as 3 ft. per min. if a satisfactory product is to be obtained.

As a general rule, with the copper alloys the lowest extrusion temperature consistent with the alloy, extrusion ratio and power available is preferred for the following reasons:

1. The tendency for deterioration of the surface of the billet during preheating is reduced.
2. Liquid phases at grain boundaries are avoided.
3. A finer structure is obtained.
4. Transverse cracking with $\alpha + \beta$ brasses is avoided.
5. The mechanical properties throughout are more uniform.
6. The tendency for grain growth to occur on reheating is considerably reduced.

With aluminum alloys the optimum extrusion temperature naturally varies according to the ratio of reduction of area, the complexity of the shape of the section, and the alloy being extruded. In general, the temperature should be as low as practicable, although not too low to promote grain growth which may occur on subsequent heat treatment of higher strength alloys.

(Continued on p. A-176)

High Vacuum Furnaces...

Built by People Who Run Them



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1836-1954

Extrusions . . .

(Continued from p. A-174)

A great number of aluminum alloys can be effectively heat treated by the simple technique of quenching at the die. With adequate inspection and proper design of quenching equipment and safeguarding the extrusion tools, this process may be used with confidence. Separate solution treatment, as carried out in electrically or gas heated furnaces, requires proper control of the weights of loads, soaking periods and loading practices to produce satisfactory results. It is certain that the atmosphere of the solution treatment furnace has profound effect on the development of blisters in extruded sections, and it is known that the introduction into the furnace atmosphere of creosote oil or ammonium fluoride vapor or the greasing of sections before being put into furnaces will markedly reduce this blistering effect.

T. F. McCORMICK

Evaluate Oxalic Acid Etching Test*

THIS PAPER summarizes the results of independent investigations by 18 laboratories on a method of testing certain stainless steels for their ability to resist corrosion penetration. This method of testing was proposed by M. A. Streicher of E. I. du Pont de Nemours and Co., Inc., Wilmington, Del., in his paper, "Screening Stainless Steels From the 240-Hour Nitric Acid Test by Electrolytic Etching in Oxalic Acid", A.S.T.M. Bulletin, February 1953, p. 35. The cooperative testing program was conducted under the auspices of Subcommittee IV on Methods of Corrosion Testing of A.S.T.M. Committee A-10 on Iron-Chromium and Iron-Chromium-Nickel Alloys.

At the request of F. L. LaQue, chairman of A.S.T.M. Subcommittee IV, the Engineering Research Laboratory of E. I. du Pont de Nemours and Co., Inc., supplied each of the 18 laboratories with seven specimens

(Continued on p. A-178)

*Digest of "Results of Cooperative Testing Program for the Evaluation of the Oxalic Acid Etching Test", by M. A. Streicher, A.S.T.M. Bulletin, January 1954, p. 63 to 67.

VANCORAM PRODUCTS



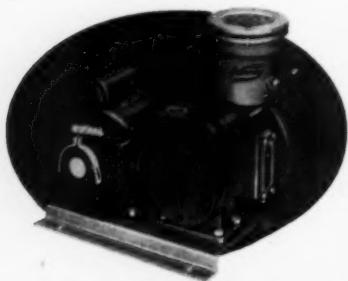
PRODUCT	TYPICAL COMPOSITION	APPLICATIONS	PRODUCT	TYPICAL COMPOSITION	APPLICATIONS
ALUMINUM ALLOYS					
Alsifer	Aluminum 20% Silicon 40% Iron 40%	Used principally as a steel deoxidizer and for grain size control.	SILICON ALLOYS (continued)	Silicon 74.79%	For high content silicon steels.
Deoxidizing Grades	Aluminum 85 to 99%	Standard grades.	75% Grade	Silicon 80.84.9%	For high silicon addition to steel; for slag treatment and graphitization of iron; for making magnesium.
Silicon Aluminum	Silicon 5 to 20% Aluminum Bal.	For sand, permanent mold and die casting.	80/85% Grade	Silicon 85.89.9%	
Titanium Aluminum	Titanium 2 1/2 and 5% Aluminum Bal.	For grain refinement and improved physical properties of commercial aluminum alloys.	85/90% Grade	Silicon 90.95%	
Vanadium Aluminum	Vanadium 2 1/2, 5, 10% Aluminum Bal.	For control of thermal expansion, electrical resistivity, and grain size of commercial aluminum.	90/95% Grade	Silicon min. 96%	For making aluminum, other non-ferrous alloys and silicones.
BORON ALLOYS					
Ferroboron	Boron 14.18% Carbon 1.50% Silicon max. 5.00% Aluminum max. 0.10%	For adding boron to steels and irons.	SPECIAL FOUNDRY ALLOYS		
Vanadium Grainal No. 1	Vanadium 25.00% Aluminum 10.00% Titanium 15.00% Boron 0.20%	Practical and economical intensifiers, for controlling and increasing the capacity of steels to harden, and for improving other important engineering and physical properties.	Graphidox No. 4	Silicon 48.52% Titanium 9.11% Calcium 5.7%	Graphitizer for high strength cast irons; reduces chill; supplementary deoxidizer for cast steel.
Grainal No. 79	Aluminum 13.00% Titanium 20.00% Zirconium 4.00% Manganese 8.00% Boron 0.50% Silicon 5.00%		Noduloy Alloys (Various Types)	Magnesium 5.16.5% Silicon 37.67% Copper 0.18% Iron Bal.	Magnesium-containing alloys for addition to molten cast iron for manufacture of nodular iron.
CHROMIUM ALLOYS					
Ferrochromium Briquettes	Hexagonal. Weigh approx. 3 1/2 lb., contain 2 lb. of chromium.	A practical and convenient form for adding ferrochromium to the cupola.	V-5 Foundry Alloy	Chromium 38.42% Silicon 17.19% Manganese 8.11%	To reduce chill and increase strength and hardness of cast iron.
High Carbon Grade	Chromium 66.70% Carbon 4.6%	For wrought constructional steels and steel and iron castings.	TITANIUM ALLOYS		
Iron Foundry Grade	Chromium 62.66% Carbon 4.6% Silicon 6.9%	For alloyed cast irons. Ladle addition readily soluble at lower temperatures of cast iron.	Ferrotitanium High Carbon Grade	Titanium 15.18% Carbon 6.8%	To control rimming action and deoxidize steel.
Low Carbon Grades	Chromium 67.72% Carbon 0.06%, .10%, .15%, .20%, .50%, 1.00% and 2.00% max.	For low carbon chromium steels, especially those with high chromium content, such as stainless steels and heat-resistant types.	Medium Carbon Grade	Titanium 17.21% Carbon 3.450%	To deoxidize and to add titanium to killed steels.
Exlo Max. .025 Carbon Grade	Chromium 67.72% Carbon max. 0.025% Silicon max. 1.00%	A special extra low carbon ferrochromium with high chromium to carbon ratio, high density and exceptional cleanliness. Especially adapted for use in .03 C max. stainless and other stainless steels, heat resistant and alloy type metals.	Low Carbon Grades 25% Titanium	Titanium 20.25% Carbon max. 0.10% Silicon max. 4.00% Aluminum max. 3.50%	Carbide stabilizer in high chromium corrosion-resistant steels of extremely low aluminum content. Deoxidizer for some steels.
Max. .06 Carbon Grade	Chromium 67.72% Carbon max. 0.06% Silicon max. 1.00%	A special low carbon ferrochromium similar in characteristics to max. .025% carbon grade but for use where the extra low carbon content is not as essential.	27/32% Titanium (Various Types)	Titanium 27.32% Carbon max. 0.10% Silicon max. 4.00% and 5.00% Aluminum max. 1.50 to 5.00%	Alloy of high titanium-to-aluminum ratio for adding relatively large amounts of titanium to stainless and heat-resistant steels.
Low Carbon Ferrochrome-Silicon	Chromium 39.42% Silicon 40.42% Carbon max. 0.05%	Used in stainless steels to reduce chromium oxide from slag and to add chromium to steel.	40% Titanium	Titanium 38.43% Carbon max. 0.10% Silicon max. 4.00% Aluminum max. 8.00%	Carbide stabilizer in high chromium corrosion-resistant steels.
Experimental Ferrochrome-Silicon Alloy	Chromium 48.52% Silicon 25.30% Carbon max. 1.50%	For simultaneous addition of chromium and silicon to low alloy steels and cast iron.	VANADIUM ALLOYS		
SILICON ALLOYS					
Ferrosilicon Briquettes	Two sizes, both cylindrical. The smaller contains 1 lb. of silicon; the larger, 2 lbs. of silicon.	A practical and convenient form for adding ferrosilicon to the cupola.	Ferrovanadium Iron Foundry Grade	Vanadium 38.42% Silicon 7.11% Carbon about 1%	Imports remarkable improvement in physical properties of iron with no sacrifice of machinability.
25% Grade	Silicon 22.26%	To deoxidize open hearth steels and add silicon to cast iron.	Grade A (Open Hearth)	Vanadium 50.55% Silicon max. 7.50% Carbon max. 3.00%	For low vanadium steels and vanadium cast irons.
50% Grade	Silicon 47.52%	To deoxidize and add silicon to steels and cast irons.	Grade B (Crucible)	Vanadium 50.55% Silicon max. 3.50% Carbon max. 0.50%	For tool steels and other high vanadium steels requiring a limited silicon addition.
Silblok 25 & 50	Same as above	Blocking grades especially processed to give high density, uniform analysis, greater cleanliness.	Grade C (Primos)	Vanadium 50.55% 70.80% Silicon max. 1.25% Carbon max. 0.20%	For making the highest vanadium and the lowest silicon addition to tool steels.
65% Grade	Silicon 62.67%	For deoxidation and for addition of silicon to high silicon steels.	Vanadium Metal 90% Grade	Vanadium 91.15% Aluminum 2.25% Silicon 0.50% Carbon 0.17%	For special iron-free (non-ferrous) or low iron alloys or low impurity ferrous alloys.
			99.7% Grade	Vanadium 99.7%	Principally for research on the properties of pure alloys.
			Vanadium Pentoxide, Tech. Fused Form	V ₂ O ₅ 88.92%	A source of vanadium in basic electric furnace steels. A base for numerous chemical compounds.
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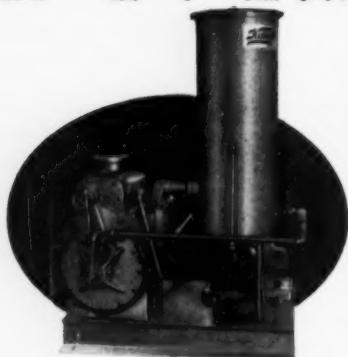
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Etching Test . . .

(Continued from p. A-176)
in duplicate of Types 304 and 316 mill annealed, 304, 304 L (low carbon) and 316 annealed and sensitized by heating 1 hr. at 1250° F. followed by a water quench. Testing consisted of:

1. Boiling nitric acid tests on all seven specimens.

2. Electrolytic etching tests on the seven duplicate specimens with preparation of seven micrographs.

The proposed method is intended for use as a screening method to substitute for the boiling nitric acid test for corrosion resisting steels. Specification A 62, A.S.T.M. Standards 1952, Part 1, p. 998.

This test consists of five separate boiling periods, each of 48 hr. duration, with drying and weighing at the end of each 48 hr. In some instances the specification permits testing to be stopped after a minimum of 3 periods of 48 hr. From these tests calculations of corrosion rates in inches penetration per month

are made. Elaborate precautions must be taken to have uniformly representative samples free of surface contaminants and with a uniform condition of surface finish.

In the oxalic acid test the specimen is merely given a reasonably good metallographic polish and the polished surface is etched at room temperature in a 10% (by weight) solution of oxalic acid for 1 1/2 min. using a current density of 1 amp. per sq. cm. For the sake of reproducibility the conditions of the test should be precisely controlled. Photographs are made at a magnification between 250 and 500 and the photomicrographs of the etched structures are then evaluated according to the following criteria:

1. Step structure — steps only at the grain boundaries.

2. Ditch structure — one or more grains in a given field completely surrounded by ditches.

3. Dual structure — a combination of the above two.

Materials showing step or dual structure are assumed to have a rate

(Continued on p. A-180)

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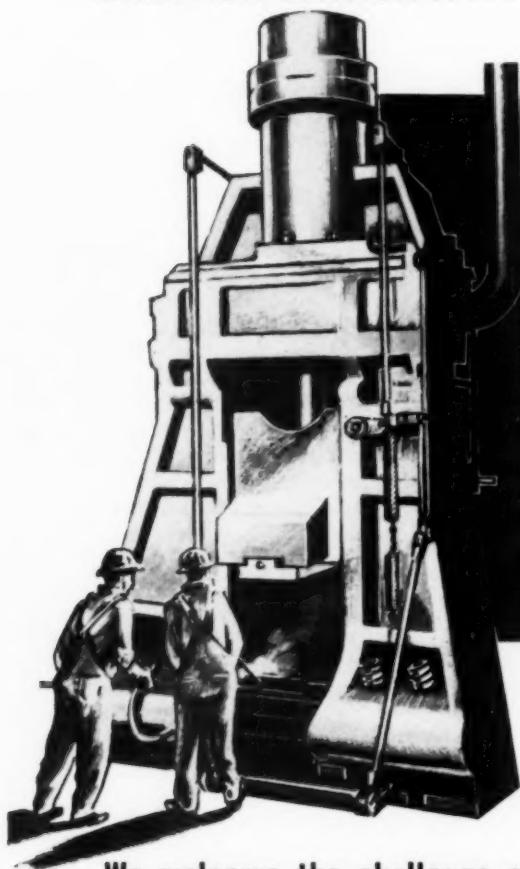
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Etching Test . . .

(Continued from p. A-178)
of corrosion penetration which is less than the maximum permissible rate for the type of steel, while those showing ditching will be assumed to have a failing rate under the standard practice tests.

There was complete agreement among the cooperating laboratories in the interpretation of clear-cut step

or ditch structures but there was some disagreement in interpreting the dual structures. (The photomicrographs reproduced with the report seemed to this reviewer to be easy to evaluate.) It appears that ditching would be closely associated with susceptibility to grain-boundary attack. In only one instance (Type 316) would the procedures as applied have resulted in the release of a steel which had a penetration rate higher than that allowed in the

specifications. With reference to this steel, Dr. Streicher comments that its acceptance should be limited to specimens showing step structure only. This would have avoided the erroneous acceptance of the above specimen. From the summary of the boiling nitric acid tests the variation in results was nearly tenfold between two observers on a single specimen not passing the test. The range in corrosion rate for this specimen was from 0.0205 to 0.00268, both values being above the acceptance level of 0.0015 in. per month.

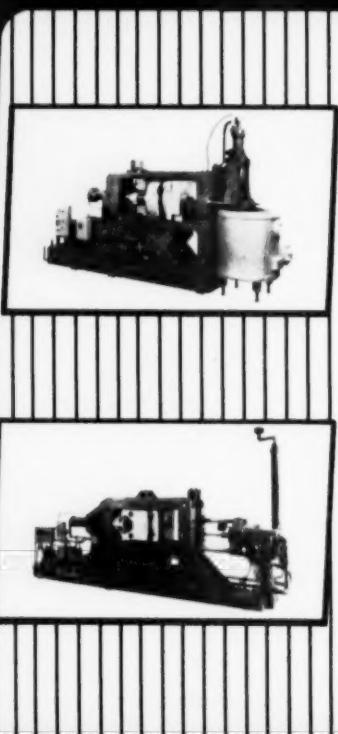
Conclusions — There was complete agreement among the 18 participants that five of the seven specimens would have passing corrosion penetration tests and that the other two specimens would have failing rates based on the oxalic acid screening procedure. The validity of these screening procedures was checked by actually making the boiling nitric acid test and tabulating the results.

Steels showing a step or dual structure will have a corrosion penetration rate less than that specified for the boiling nitric acid test and need not be subjected to the 240-hr. test, except Type 316 steel. Specimens which show ditching all the way around one or more grains in a given field should be subjected to the boiling nitric acid test.

The application of the oxalic acid electrolytic etching test would eliminate the necessity for the 240-hr. test with boiling nitric acid in a large percentage of the specimens examined. There appears to be little chance of material being accepted which would show excessive weight loss on the long test.

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Deoxidation of Iron by Silicon*

THE PROCEDURE used in this study of the effect of silicon additions to pure iron was to melt 18 heats of iron of about 300 to 400 g. each in sintered alumina crucibles in an evacuated high-frequency furnace. To each melt a fixed addition of oxygen was made by placing a weighed quantity of ferric oxide in a plugged hole at the base of the iron charge. After melting, granular silicon of high purity (0.032% insoluble content, 0.025% Al, 0.045% Ca) contained in a small capsule of iron sheet was added by means of a magnet from a side arm in the furnace superstructure.

The temperature in the melt was not permitted to rise above 2900° F. Sufficient time was allowed for the silicon addition to become thoroughly mixed with the iron, the power was switched off, and the mold was solidified and cooled under vacuum.

A microscopic examination was made of a complete longitudinal half-section of one of the ingots in which large additions of oxygen and silicon were made, to determine the segregation of the inclusions. A gross segregation of inclusions was found in the top of the ingot and this was removed prior to subsequent examination; the remainder of the surface was thoroughly filed to remove any refractory and oxide coating.

The ingots were then quartered longitudinally and samples were taken as follows: (a) cylindrical pieces for vacuum fusion analysis from the center of the ingot; (b) slices 1 mm. thick for alcoholic iodine extraction (one 10-g. sample for X-ray examination and two 10-g. samples for chemical analysis of the residue); (c) millings for chemical analysis of silicon.

The nonmetallic residue obtained from the iodine extractions was analyzed for SiO_2 , FeO and Al_2O_3 and the percentage of oxygen in each of these oxides was tabulated. The total oxygen obtained from the vacuum-fusion analysis is also shown, (Continued on p. A-184)

*Digest of "Studies in the Deoxidation of Iron; Deoxidation by Silicon", by E. Ll. Evans and H. A. Sloman, *Journal of the Iron and Steel Institute*, November 1952, p. 296-300.

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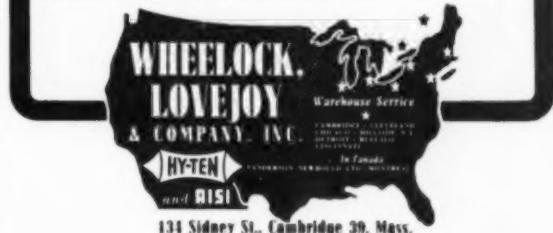
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Deoxidation . . .

(Continued from p. A-182) the total oxygen in the oxides of the residue and the difference between these assumed to be oxygen in the melt. The total silicon content of the sample minus the silicon in the SiO_2 of the residue gives the total silicon in the melt. The melts of the first 12 heats had less than 0.10% Si. The remaining heats had silicon additions giving a residual silicon varying from 0.26 to 0.85%.

The nature of the deoxidation products was determined by X-ray diffraction studies of the extraction residue and by microscopic examination of the metal. When the silicon content was less than 0.10%, it was found that the inclusions consisted of mixtures of FeO and SiO_2 with varying amounts of wüstite (FeO) and fayalite ($2\text{FeO} \cdot \text{SiO}_2$); the melts containing over 0.10% silicon invariably contained inclusions which consisted of pure SiO_2 . This interesting observation seems to indicate the reason why so many of the semi-killed steels contain less than 0.10%

silicon and also demonstrates why silicon additions greater than 0.10% cause surface difficulties in the rolling of steel which is deoxidized only with silicon.

The calculated oxygen in each of the melts is plotted against the residual silicon in the melt for comparison with the silicon-oxygen equilibrium curve reported by Gokcen and Chipman. All of the points recorded from data for these tests are below the equilibrium line shown by Gokcen and Chipman in their published curves.

The conclusions of the authors are that the principal product of the deoxidation of iron by silicon, when silicon is in stoichiometric excess of oxygen, is practically pure silica. As the residual silicon content of the iron decreases below 0.10%, the slag phase with which the iron is in equilibrium increases in iron oxide content.

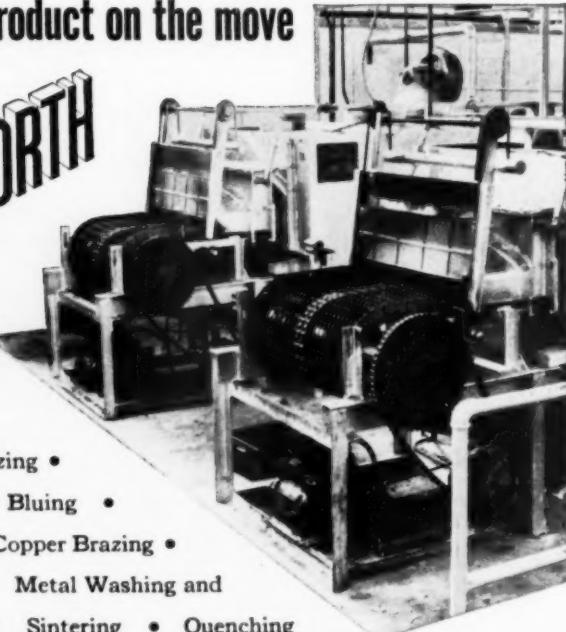
No difficulties were encountered in the use of the alcoholic iodine extraction method for the isolation of the inclusions formed in the melt by deoxidation with silicon.

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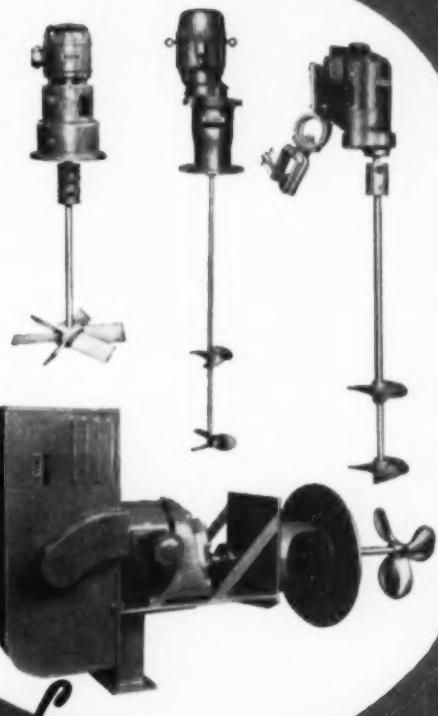
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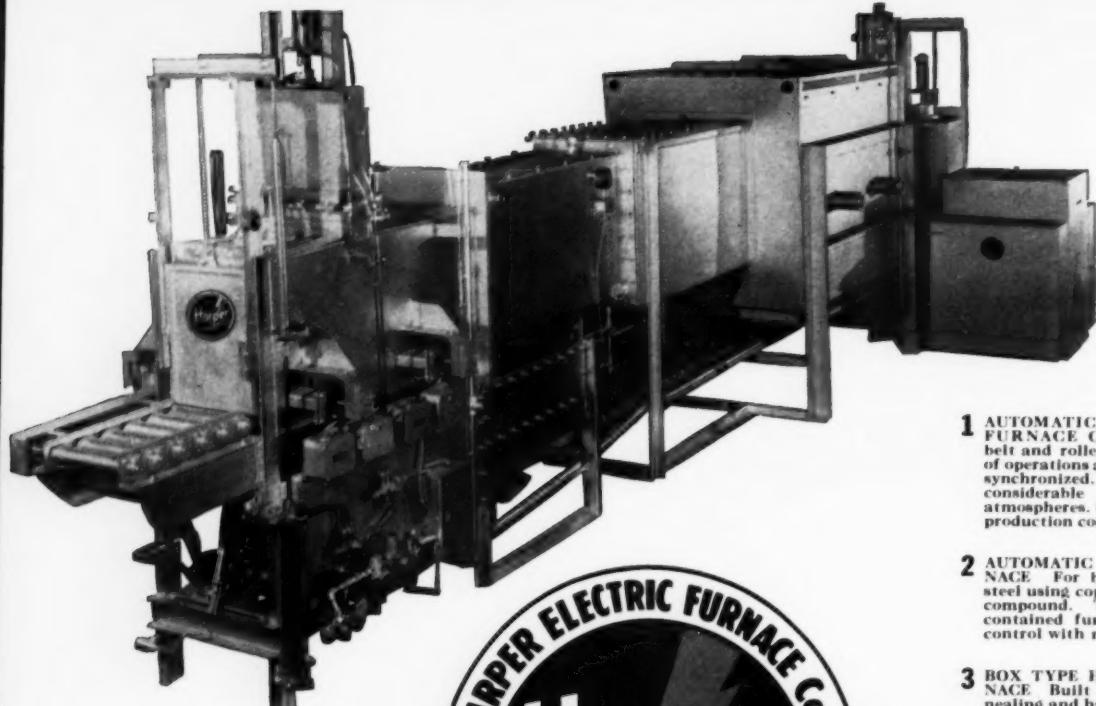
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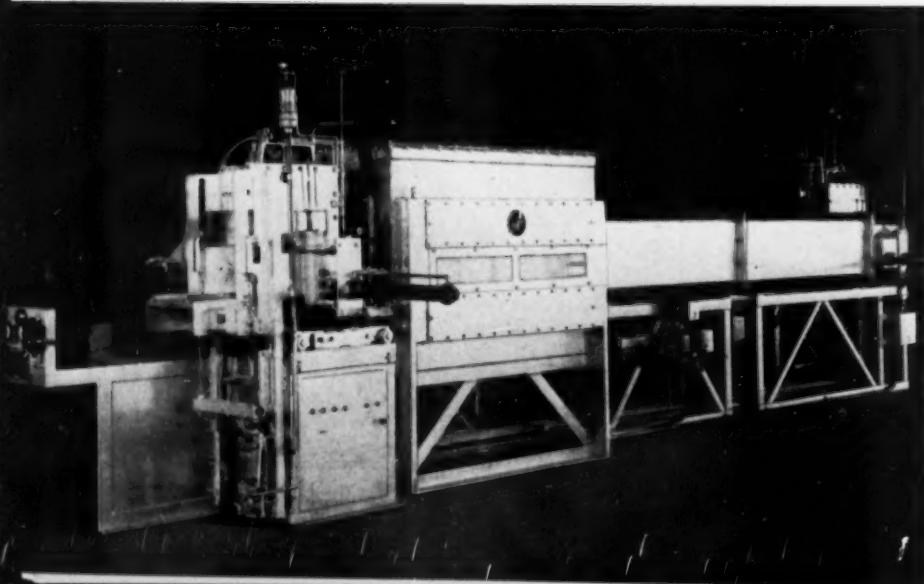
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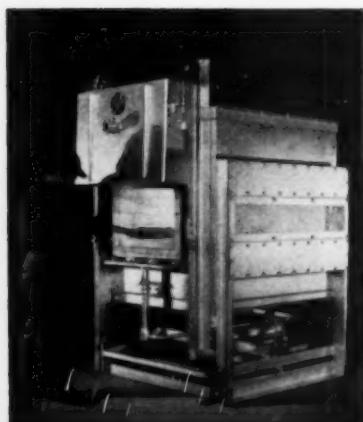
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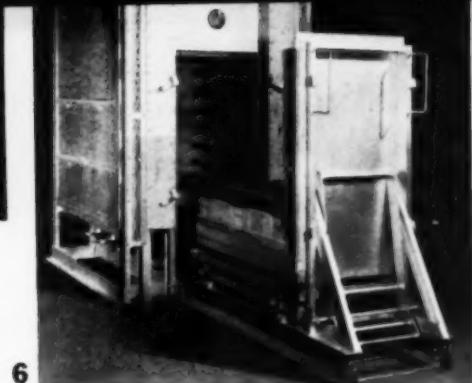
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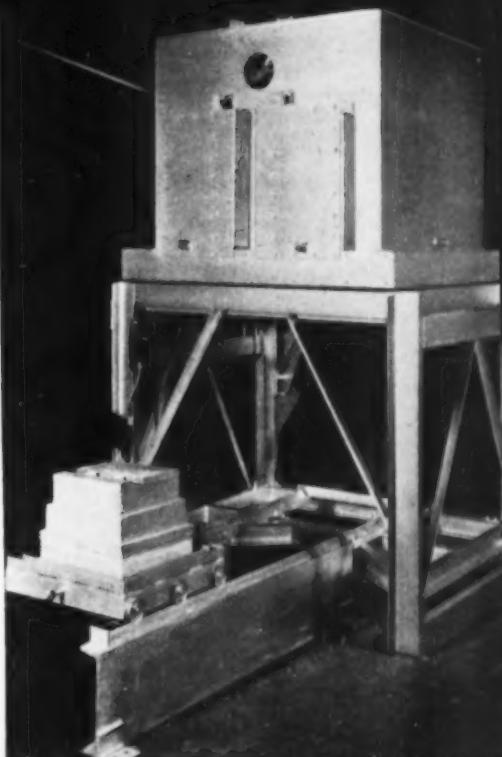
- Mesh Belt
- Pusher Type
- Bell
- Elevator
- Pit
- Car Bottom
- Box
- Continuous Wire and Strip Annealer
- Roller Hearth
- Rotary Hearth

PROCESSES

- Continuous Brazing
- Sintering
- Bright Annealing
- Stainless Steel
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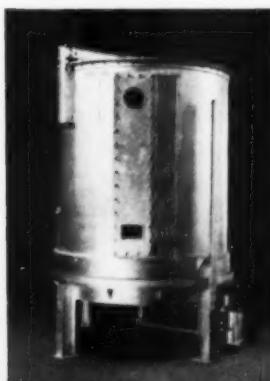
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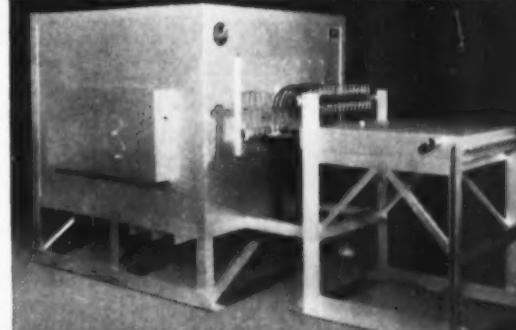
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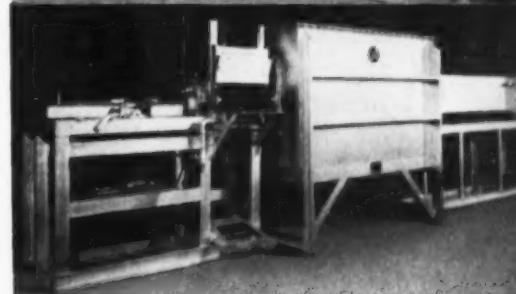
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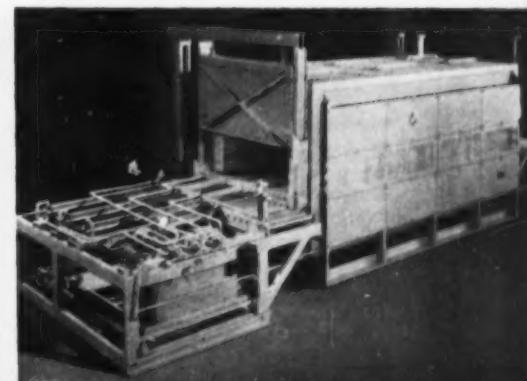
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Stretcher-Strain Marks in Al-Mg Alloys*

ALUMINUM alloys containing 3 to 7% magnesium sometimes cause trouble during forming because of stretcher-strain markings that result from the pressing or drawing operation. These markings are of two kinds: readily visible wedge-type marks, similar to Lüders marks on steel and called "Type A"; and shallow parallel ripples, less apparent, called "Type B". By ingenious testing techniques, it is possible to study each of these kinds of marks separately and thus to deduce their nature and cause.

Type A is the more serious defect. It occurs in fine-grained, recrystallized, annealed materials, often in regions of very slight strain, and appears to be a yield-point effect. Stress-strain diagrams of annealed commercial sheet containing about 3½% magnesium have a relatively large initial yield either at or soon after the start of plastic deformation, followed by multiple yielding evidenced by a number of smaller steps. Tensile test specimens show that severity of Type A marking correlates closely with size of the large initial yield; furthermore, that the flange of the Erichsen cup specimens of the same material shows the same wedge-type markings. Good correlation between stress-strain curve, Erichsen specimens, and shop experience is shown in the following tabulation for four commercial aluminum alloys containing 3½% magnesium.

ELONGATION AT EARLY YIELD	MARKINGS*	
	A	B
0.35%	Slight	None
0.56	None	Slight
1.07	Severe	Severe
1.29	Severe	Severe

*A—During normal processing;
B—in Erichsen test.

Type A marks do not occur in cold worked material, nor in sheet with grain size above 0.03 to 0.04 mm. Even 10% reduction is enough to prevent the appearance of Type (Continued on p. A-190)

*Digest of "Yield-Point Phenomena and Stretcher-Strain Markings in Aluminium-Magnesium Alloys", by V. A. Phillips, A. J. Swain and R. Eborall, *Journal of the Institute of Metals*, Vol. 81, 1952-53, p. 625 to 647.

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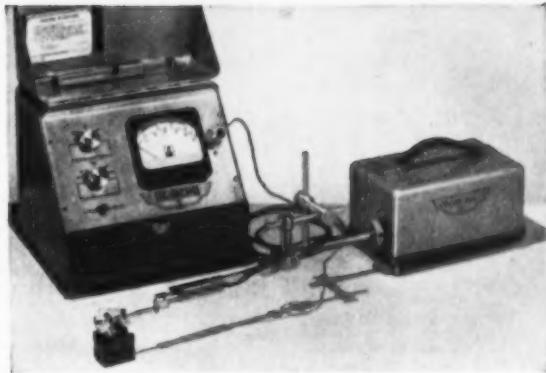
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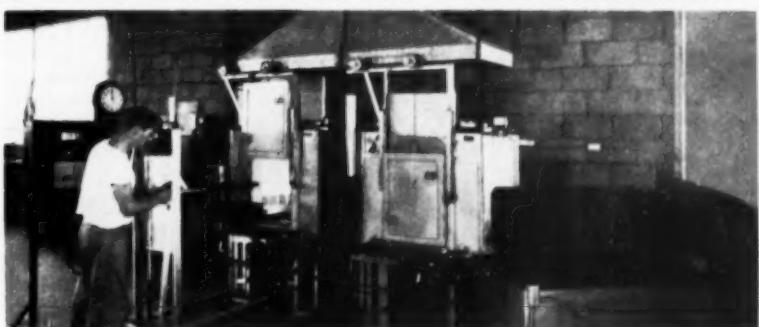
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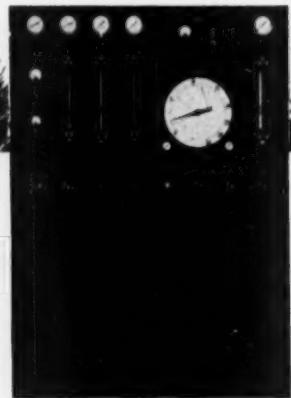
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Stretcher-Strains . . .

(Continued from p. A-188)
A wedge marks, and of the large initial yield on the stress-strain curve. Type A marks can also be avoided by heating to 932° F. and water quenching, but reappear if the material is reheated.

Type A wedge marks are a shear mechanism, corresponding to the first spread of yielding into undeformed grains. Since magnesium atoms are large, they collect in the grain boundary and stabilize that structure, retarding the spread of yielding from grain to grain. Cold worked material, having already been deformed, does not offer this effective barrier to yielding and, therefore, does not exhibit the Type A marks. The significance of the magnesium concentration in the grain boundaries, insofar as large initial yield and Type A marks are concerned, is shown by tests on material water quenched from 932° F. Although not cold worked, and of the same grain size as before, the quenched specimens do not show the large initial yield or the Type A marks because the magnesium is evenly distributed between the grains and the grain boundaries. Reheating such materials and thus permitting the magnesium to concentrate at the grain boundaries, brings about their reappearance.

Four methods are suggested for the prevention of Type A marks during forming of sheet:

1. Controlling grain size at 0.04 to 0.06 mm. (Larger grain size is subject to serious "orange peel" defect.)
2. Overstraining by moderate roller-leveling.
3. Overstraining by heavy roller-leveling or light rolling (about 5% reduction) followed by a nonrecrystallizing anneal.
4. Quenching from 932° F. followed by flattening.

All four of these techniques have been found to be effective in commercial operations. For applications where maximum ductility is required, such as severe drawing, treatments involving overstraining followed by a nonrecrystallizing anneal, or quenching from elevated temperature followed by flattening, are especially recommended.

Type B markings are not so easily seen as Type A wedge-marks,

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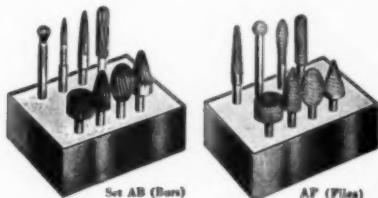
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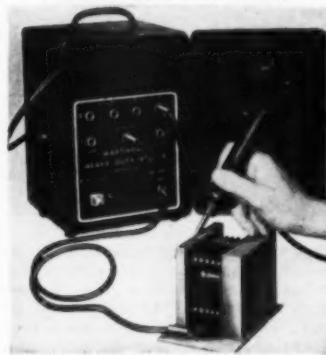
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and are seldom cause for rejection of parts. These appear as shallow parallel ripples in highly stressed areas; their occurrence coincides with the numerous small steps in the stress-strain curve, while the Type A marks correspond to the large initial yield. Unlike Type A wedge marks, Type B ripples bear no relation to the Erichsen test, are not affected by grain size, and are found on cold worked material as well as on soft stock. Type B markings are, therefore, thought to be a strain-aging phenomenon. Tests made at lower temperatures (-85 and -100° F.) are smooth and free from the many small steps which characterize the Type B yielding and markings at room temperature; these became fainter with decreasing temperatures and were not visible on the tests made at -100° F.

Type B strain aging is not a true precipitation or age hardening, for it does not result in raising the whole level of the stress-strain curve. It is explained by applying to aluminum-magnesium alloys the theory that Cottrell proposed for steel—the magnesium dissolved in the aluminum, being a substitutional solute in a face-centered cubic metal, effectively blocks the initiation of slip until a certain stress is exceeded. Since Type B marks are shallow they do not present a serious defect from the production point of view.

REBECCA H. SPARLING

Alloys for High Temperatures*

This investigation was undertaken to study the fundamental factors responsible for high-temperature strength. At the time this program was started, one of the best high-temperature alloys available was the cobalt-chromium base alloy, Vitallium; therefore, the relationship between the structure and properties was studied for this alloy. Because of the complexity of Vitallium, the phase relationships in the binary and ternary systems had to be studied

*Digest of "Alloys for High-Temperature Service (Investigation of the Fundamental Factors Promoting High-Temperature Strength of Alloys)", by R. L. Beck, E. E. Fletcher, A. R. Elsen, A. B. Westerman and G. K. Manning, Battelle Memorial Institute, March 1952, ATI-166644.

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L-12



High Temperatures . . .

(Continued from p. A-191)
before starting a structural analysis.

The cobalt-chromium binary system and the effects of ternary additions, such as nitrogen, iron, nickel, molybdenum, and tungsten, were studied by metallographic and X-ray diffraction techniques. It was found that the phases pertinent to Vitalium were alpha, beta and gamma phases. The alpha phase is the high-temperature modification of the cobalt-rich terminal solid solution and has a face-centered cubic lattice. The alpha phase transforms on cooling to the beta phase which has a hexagonal close-packed lattice.

Examination of the binary diagram developed by the authors indicated that the addition of chromium to cobalt raised the temperature range for the alpha-beta transformation. The single beta phase occurs in a narrow band 45 to 93° F. wide. Below this band of beta, gamma phase was precipitated. The gamma phase is a brittle intermetallic compound of cobalt and chromium, Co_2Cr_3 , having a complex crystal structure. The additions of nitrogen, iron or nickel lowered the alpha-beta transformation temperature range. The addition of tungsten had little effect on the alpha-beta transformation temperature range, but it did raise the temperature at which gamma phase started to precipitate. Additions of molybdenum raised the temperature range for the alpha-beta transformation and the temperature at which gamma phase started to precipitate.

The minor phases in Stellite No. 21 (Vitalium) were identified as gamma phase (Co_2Cr_3), chromium carbide (M_{23}C_6), a complex double carbide (M_6C) and a simple chromium carbide (Cr_7C_3). The upper limit of the alpha-beta transformation in Stellite No. 21 was about 1830° F. Because of the sluggish reactions, the lower limit of the range was not determined but was estimated to be about 1290° F.

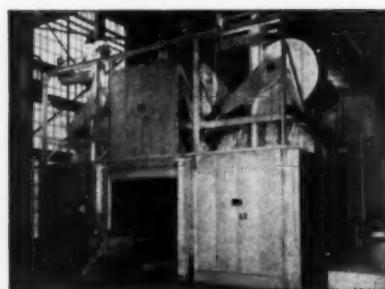
In the cobalt-chromium binary alloys, some of the alloys had a lower creep rate at higher stresses at a given temperature. This was attributed to the strengthening effect of the smaller gamma particles precipitated at high stresses. The tests

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also showed that a higher prestress at a given temperature resulted in a lower creep rate; this may have been influenced by the precipitation of submicroscopic particles. The precipitation of submicroscopic particles would also account for the contraction that was frequently observed just prior to second-stage creep. In the creep-rupture tests, an increase in chromium, carbon, or nitrogen increased the creep resistance at all temperatures tested. The alpha and beta phases had about the same strength but a mixed alpha-beta structure was weaker.

Creep-rupture tests of Stellite No. 21 at 1500° F. showed that the as-cast material was stronger than the homogenized or the homogenized and aged material. The strength of the as-cast material was improved by aging. The homogenized material decreased in strength when aged at 1335° F., although this aging treatment resulted in an increase in hardness. Variations in carbon, nickel or molybdenum had little effect on the aging characteristics.

R. E. LOCHEN

Protective Behavior of Paint Primers

A COMPARISON was made of the behavior of four pigments when used in a primer coat for aluminum, magnesium alloys and mild steel. Comparison was based on the relative protection from corrosion of untreated metal panels and chromated metal panels when coated with primer alone and also coated with primer and finish coat. The four pigments were red lead, iron oxide, zinc chromate, and zinc tetroxy-chromate. Each pigment was incorporated into a varnish made with a phenolic resin and a combination of linseed and oiticica oils to produce the four primers. Two types of finish coats were used; one was based on an oil-modified alkyd resin and the other on a nitrocellulose-alkyd resin combination. The finish coats were

*Digest of "Priming Paints for Light Alloys", by J. D. Rigg and E. W. Skerrey, *Journal of the Institute of Metals*, Vol. 81, 1952-53, p. 481-489.

pigmented with aluminum powder.

The metals tested conformed to the following specifications:

Aluminum: 0.24 Si, 0.31 Fe, 0.008 Cu, 0.008 Mn, 0.010 Zn.

Aluminum, B.S.S. 5L3: 0.54 Si, 0.40 Fe, 3.95 Cu, 0.59 Mn, 0.018 Zn, 0.60 Mg.

Magnesium (high purity), D.T.D. 120a: 0.006 Si, 0.0005 Fe, 0.006 Cu, 0.42 Mn, 0.93 Zn, 6.10 Al.

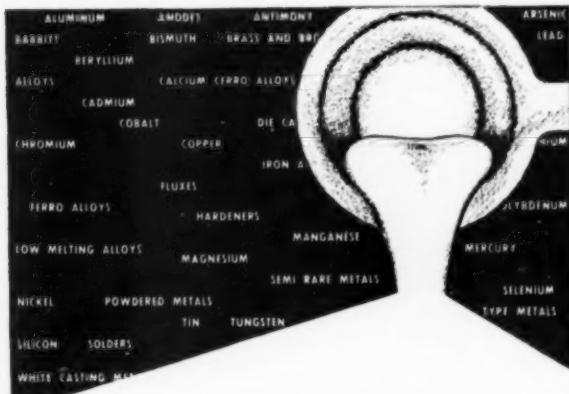
Magnesium (normal purity), D.T.D. 118: 0.005 Si, 0.021 Fe, 0.004 Cu, 1.54 Mn, 0.005 Zn.

Magnesium (normal purity), 59a: 0.010 Si, 0.022 Fe, 0.002 Cu, 0.28 Mn, 0.59 Zn, 7.70 Al.

Magnesium (high purity), 59a: 0.010 Si, 0.0010 Fe, 0.002 Cu, 0.18 Mn, 0.58 Zn, 7.83 Al.

Mild steel: 0.18 C, 0.040 S, 0.26 Mn, 0.027 P, 0.01 Si

The uncoated and coated metal panels were exposed under the following four conditions: accelerated tests, marine conditions, industrial conditions, and rural conditions. The panels were examined after exposure for six months and again after exposure for 3½ years. The present



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paper gives the results from the 3½ years' exposure; the six months' test was reported previously.

Since the principal object of this work was to compare the four pigments for use in metal primers, no mixtures with extender pigments were used. (In actual practice it is often customary to add an extender pigment, such as magnesium silicate, to reduce the gloss on the primer so as to promote better adherence between primer and finish coats.) Since no extender pigments were used in these tests, the primers based on zinc chromate, zinc tetroxychromate, and iron had higher than normal gloss and showed flaking of the finish coat to various degrees after exposure. There was practically no flaking over the red lead primer because this had a dull or matte finish.

Rapid failure of the red lead primers occurred over aluminum and especially over the magnesium alloys (about six weeks under marine conditions) which provided further evidence that red lead should not be used in primers for light metals. In the presence of moisture a chemical reaction occurs between the red lead

and the light metal that reduces the red lead and disrupts the coating. In view of this situation the red oxide primers were greatly superior to red lead primers on light metals. They gave good protection as long as the films were intact, but they did not inhibit corrosion if the film was damaged in any way. The best protection was obtained with primers containing zinc chromate or zinc tetroxychromate. These pigments have corrosion inhibiting properties on light metals and steel; therefore, they prevent the spread of corrosion under the coatings at breaks or damaged locations. The results indicated little or no difference between zinc chromate and zinc tetroxychromate for use in corrosion inhibiting primers.

Both types of zinc chromate were found to be slightly better than red lead in primers on mild steel. The red oxide primer gave good protection but did not inhibit corrosion where the film was broken. For composite structures of steel and light alloys, the zinc chromate or zinc tetroxychromate primers were preferred. It was suggested that the red oxide primer may be suitable under con-

ditions of mild exposure. It is also possible that combinations of the zinc chromate pigments and red oxide pigments would be satisfactory and effect an economy in cost.

It was observed that the alkyd resin finish coat showed less tendency to flake than the nitrocellulose finish from the primer coat. As indicated previously, improved adherence would have been obtained if the primer had had less gloss.

A comparison of the satisfactory paint systems on steel and the light metals showed better durability and less corrosion on the light metals. This comparison excluded the red lead primer systems on light metals because it should not be used for these. As may be expected the accelerated test with sea-water spray and the marine exposure were the most severe conditions of exposure. However, the results indicated that satisfactory paint systems may be formulated for light metals which show only slight corrosion after 3½ years of exposure. The same paint systems on steel showed equal corrosion in from one to two years.

H. F. PAYNE

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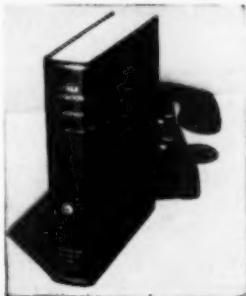
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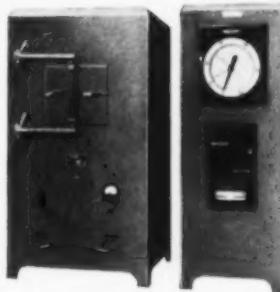
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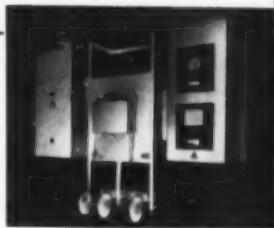
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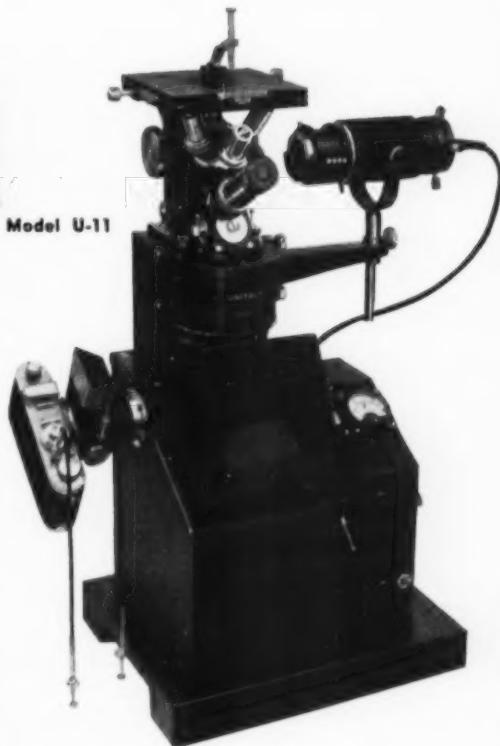
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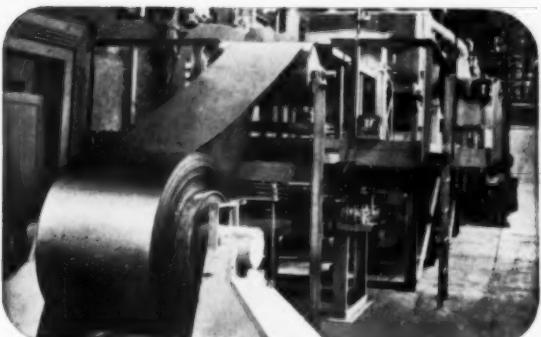
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• Index to Advertisers •

Acme Machinery Div.	A-149	Gas Machinery Co.	A-134	Niagara Alkali Co.	A-44
Acme Manufacturing Co.	A-133	General Alloys Co.	A-167	Nitralloy Corp.	A-66
Air Reduction Sales Co. Inc.	A-14, A-15	General Electric Co.	A-8, A-9	Nitrogen Div., Allied Chemical & Dye Corp.	A-100
Ajax Electric Co.	A-19	G. E. X-Ray Co.	A-83	North American Mfg. Co.	A-43
Ajax Electrothermic Corp.	A-127	Gordon Co., Claud S.	A-184	Northwest Chemical Co.	A-95
Ajax Engineering Corp.	A-16	Great Lakes Carbon Corp.	A-183	Norton Co.	A-6, A-7
Ajax Manufacturing Co.	A-50	Gries Reproducer Corp.	64	Oakite Products, Inc.	A-173
Aldridge Industrial Oils, Inc.	54, 60	Handy & Harman	A-41	Ohio Crankshaft Co.	A-45
Allegheny Ludlum Corp.	A-81	Hangerster's Laboratories	61	Ohio Steel Foundry	A-152
Allied Research Products, Inc.	A-108	Harper Electric Furnace Corp.	A-186, A-187	Park Chemical Co.	53, 114C
Alpine, Inc.	A-189	Hauke Mfg. Co.	A-185	Penn Brass & Copper Co.	A-31
Allmetal Screw Products Co., Inc.	A-178	Haynes Stellite Corp., Unit of Union Carbide & Carbon Corp.	A-40	Pereny Equipment Co.	A-195
Almetco Div.	58	Hayes Inc., C. I.	A-145	Pittsburgh Tool Steel Wire Co.	A-17
Alpha Corp.	61	Hays Corp.	54	Plume & Atwood Mfg. Co.	A-131
Aluminum Co. of America	A-16, A-B-C-D	Heathcoat Corp.	A-161	Pressed Steel Co.	A-89
American Brass Co.	A-105	Hell-Coll Corp.	A-38	Production Specialties, Inc.	59, A-188
American Gas Furnace Co.	A-107	Hevi Duty Electric Co.	A-27	Puritan Mfg. Co.	59
American Machine & Metals, Inc.	A-20	Himmel Brothers Co.	61	Pyrometer Instrument Co.	A-190
American Non-Gran Bronze Co.	A-183	Holcroft & Co.	A-32-B	Ransburg Electro-Coating Corp.	A-71
American Optical Co.	A-122	Holger Andreasen, Inc.	A-166	Raybestos-Manhattan, Inc., Manhattan Rubber Div.	60
American Platinum Works	A-97	Hoover Electrochemical Co.	A-125	Republic Steel Corp.	A-121
American Rack Co.	60	Hoover Co., Die Castings Div.	64	Revere Copper & Brass, Inc.	A-93
American Tank & Fabricating Co.	A-123	Houghton & Co., E. F.	A-79	Richardson Co., J. A.	63
American Welding & Manufacturing Co.	A-115	Hupp Corp., Globe Stamping Div.	A-28	Richardson Co., Inc., Arkley S.	A-194
Amplex Div., Chrysler Corp.	A-137	Illinois Testing Laboratories, Inc.	A-94	Rockwell Co., W. S.	A-112
Analytical Measurements, Inc.	A-191	Imperial Rack Co.	60	Rolled Alloys, Inc.	A-32-A
Anseco Div., General Aniline & Film Corp.	A-46	Induction Heating Corp.	A-4	Roll Formed Products Co.	61
Armour & Co., Ammonia Div.	A-68	Industrial Heating Equipment Co.	53, A-160	Roto Finish Co.	A-194
Armstrong-Blum Mfg. Co.	A-151	Industrial Back Co.	60	Ryerson & Son, Inc., Jos. T.	A-88
Ashworth Brothers, Inc.	A-184	Industrial X-Ray	A-154	Sandvik Steel, Inc.	A-77
Atlantic Chemicals & Metals Co.	60	Insulation & Wires, Inc.	A-49	Sargent & Wilbur, Inc.	A-164
Austenol Laboratories, Inc.	A-116	Ispen Industries, Inc.	A-37	Scherr Co., Inc., George	A-193
Babcock & Wilcox, Tabular Products Div.	A-32	Jarrell-Ash Co.	A-130	Schnell Tool & Die Corp.	62
Baird Associates	A-182	Jelliff Mfg. Corp., G. O.	58	Scovill Mfg. Co.	A-129
Baker & Co., Inc.	A-190	Jet Combustion, Inc.	A-148	Session & Son, J. H.	63
Baldwin-Lima-Hamilton	A-48	Jones & Laughlin Steel Corp.	A-67	Seymour Mfg. Co.	A-47
Bausch & Lomb Optical Co.	114D	Keleket X-Ray Corp.	A-30	Shenango-Penn Mold Co.	A-120
Bel-Ray Co., Inc.	61	Kerns Co., L. R.	A-141	Shieldalloy Corp.	A-118
Berkeley Smelting & Refining Works	A-193	Kent Cliff Laboratories Div., Torsion Balance Co.	56	Solventol Chemical Products, Inc.	A-5
Beryllium Corp.	A-142, A-143	Kinney Mfg. Div. of N. Y. Air Brake Co.	A-178	Spencer Turbine Co.	A-101
Bethlehem Steel Co.	A-42	Koppers Co., Inc.	A-36	Spot Testers, Inc.	A-189
Blaw-Knox Co., Natl. Alloys Div.	A-163	Kux Machine Co.	A-70	Standard Alloy Co., Inc.	A-136
Boder Scientific Co.	57	Lake Erie Engg. Corp.	A-12, A-13	Standard Steel Treating Co.	56
Bower Technical Refrigeration	A-110	L & L Mfg. Co.	A-158	Stanwood Corp.	54
Branson Instruments, Inc.	58	Lakeside Steel Improvement Co.	A-135	Star Stainless Screw Co.	63
Brooks & Perkins, Inc.	A-159	LaSalle Steel Co.	A-103	Steel City Testing Machines, Inc.	A-188
Brush Electronics Co.	A-189	Latrobe Steel Co.	A-33	Steel Improvement & Forge Co.	A-179
Bucher, Ltd.	A-80	Lebanon Steel Foundry	A-10, A-11	Stokes Machine Co.	A-169
Carborundum Co.	A-51	Lester-Phoenix, Inc.	A-180	Sunbeam Corp.	A-76
Carl-Mayer Corp.	A-192	Lindberg Engineering Co.	A-72	Sun Oil Co.	A-22
Castle & Co., A. M.	A-119	Lindberg Steel Treating Co.	A-140	Surface Combustion Corp., Inside Front Cover	
Casting Engineers, Inc.	A-168	Linde Air Products Co.	A-78	Swift Industrial Chemical Co.	54, 58
Chemical Corp.	A-192	Little Falls Alloys	63	Sylvania Electric Products, Inc.	A-144
Cires Equipment Co.	A-156	LR Heat Treating Co.	55	Technic, Inc.	58
Cleveland Crane and Engineering Co.	63	Lohdell United Co.	A-176	Technical Operations, Inc.	A-23
Cleveland Metal Abrasive Co.	60	MacDermid Co.	A-65	Thompson Products, Inc.	A-106
Consolidated Vacuum Corp.	A-24	Magnethermic Corp.	A-113	Timken Roller Bearing Co.	A-153
Continental Foundry & Machine Co.	A-18	Magnetic Analysis Corp.	57	Titan Metal Mfg. Co.	A-64-A
Cooley Electric Mfg. Corp.	55	Mahan Co., R. C.	A-99	Titanium Alloy Mfg. Div., Natl. Lead Co.	A-165
Crucible Steel Co. of America	Back Cover	Malayan Tin Bureau	A-86	Turco Products, Inc.	A-157
Deakin & Son, J. Arthur	57	Mallory-Sharon Titanium Corp.	A-64-B	Uddeholm Co. of America	A-74
Dempsey Industrial Furnace Corp.	53, A-96	Manhattan Rubber Div., Raybestos-Manhattan Inc.	60	United Scientific Co.	A-195
Detrex Corp.	A-124	Marion Co.	A-138, A-139	United States Steel Corp.	A-34, A-35
Detroit Testing Machine Co.	57	Martindale Electric Co.	A-191	Upton Electric Furnace Co.	54
Dixie Mfg. Co., J. P.	A-185	Maurath, Inc.	62	Vanadium Corp. of America	A-177
Dixie Co., J. W.	57	Medart Co.	A-128	Van Der Horst Corp.	A-98
Dieterl Co., Harry W.	A-114	Mechanite Metal Corp.	114A	Waltz Furnace Co.	A-104
Dow Furnace Co.	A-132	Meriam Instrument Co.	56	Waukesha Engineering Co.	A-174
Du-Pont Chemical Corp.	59	Metal Hydrides Co.	A-126	Waukesha Foundry Co.	A-84
duPont de Nemours & Co., Inc.	A-73, A-155, A-171, A-181	Metal Treating Institute	A-52	Western Products, Inc.	55
Ekstrand & Tholand, Inc.	62	Metals Disintegrating Co., Inc.	A-172	Westinghouse Electric Corp.	A-109
Eclipse Fuel Engg. Co.	A-85	Metawash Machinery Co.	59	Wheelock, Loveloy & Co., Inc.	A-183
Electric Furnace Co.	Inside Back Cover	Milne & Co., A.	A-69	White Metal Rolling & Stamping Corp.	62
Electric Alloys Div., American Brake Shoe Co.	A-2	Mitchell-Bradford Chemical Co.	A-146	Wirex Mfg. Co., Inc.	53
Electric Metallurgical Co., Unit of Union Carbide and Carbon Corp.	A-90, A-91	Mixing Equipment Co., Inc.	A-28	Worcester Stamped Metal Co.	A-174
Engineered Precision Casting Co.	64	Murphy Miller, Inc.	A-170	Yale & Towne Mfg. Co., Powdered Metal Products Div.	A-150
Enthone, Inc.	A-117	Murray Way Corp.	A-82	Youngstown Foundry & Machine Co.	A-111
Erico Products, Inc.	62	National Radiator Co.	A-102	Youngstown Welding & Engineering Co.	59, A-73
Erico Foundry Co.	A-147	National Rack Co.	60		
Firth Sterling, Inc.	A-39	National Research Co.	A-175		
Finn & Dreidlein Engineering Co.	A-162				



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